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Development and implementation of viable operating rules are among the most important aspects of decisions made in reservoir system management. Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) is used to suggest reservoir system operations optimized explicitly for quantitative statements of system operating objectives. Previous studies tested the feasibility of applying HEC-PRM to aid the System Operation Review and analyzed and compared three system operation alternatives. This study improved the model's representation of the Columbia River system, analyzed and developed strategic operating rules for the system, and explored the application of HEC-PRM to seasonal operations.

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Preface

This report is the result of the third phase of work on the Columbia River System by the Hydrologic Engineering Center using the Hydrologic Engineering Center's Prescriptive Reservoir model (HEC-PRM). This work was done at the request of and with partial funding from the North Pacific Division (NPD) Corps of Engineers, USACE. The majority of the study funding was from the Corps' Real-Time Water Control Research and Development Program. NPD staff provided basic data and guidance for this study.

This study was conducted by the Hydrologic Engineering Center, Davis, California. Dr. Jay R. Lund, Associate Professor of Civil and Environmental Engineering at the University of California at Davis, lead this study while at HEC on an Intergovernmental Personnel Act (IPA) assignment. Kenneth W. Kirby, Hydrologic Engineering Intern, performed data preparation, model application, post-processed results, and assisted in result interpretation and writing of the report. Mike Burnham, Chief, Planning Analysis Division, provided study direction and management. Bob Carl, senior engineer, modified HEC-PRM software and contributed to overall analysis. Richard Hayes, hydraulic engineer, and Marilyn Hurst, computer programmer, assisted in model formulation and analysis. Loshan Law performed word processing for the final report. Darryl Davis was Director of the Hydrologic Engineering Center during the conduct of the study.

Executive Summary

Report Summary

Development and implementation of viable operating rules are among the most important aspects of decisions made in reservoir system management. One application of the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) is to suggest reservoir system operations optimized explicitly for quantitative statements of system operating objectives. This report describes a third phase of analysis of Columbia River System operation by the Hydrologic Engineering Center (HEC). The first phase of HEC's Columbia River System analysis produced a preliminary mathematical model of the Columbia River System using the HEC-Prescriptive Reservoir Model (PRM) format and tested the feasibility of applying this model to aid the System Operation Review (SOR) process underway (USACE 1991). Phase II improved the representation of the Columbia River System in the mathematical model and analyzed and compared three system operation alternatives requested by the U.S. Army Corps of Engineers North Pacific Division (NPD) (USACE 1993). In this third phase, three main tasks were completed.

First, the Phase II HEC-PRM model of the Columbia River System was improved with additional hydropower penalties, a representation of system-wide hydropower demands, representation of Brownlee reservoir operations with NPD's Hydro System Seasonal Regulation Program (HYSSR) simulation results, and additional fish and recreation penalties. The locally significant modifications and additions of penalties accomplished in this work did not change the overall structure of the optimal operations suggested by HEC-PRM from those presented in the Phase II report (USACE, 1993).

The second task for this phase of work was development of preliminary strategic operating rules for the Columbia River System. This task was accomplished using the results of the HEC-PRM model for the 50-year standard inflow hydrology used in the basin wide System Operation Review (SOR) study. These HEC-PRM results were scrutinized using a variety of data display techniques and compared with existing operations represented by HYSSR simulation results. These results show operations similar to current operations, with some major exceptions in the operation of Grand Coulee, Arrow, and Duncan reservoirs. Suggestions for promising modifications to current operations are made based on comparison of HEC-PRM and HYSSR results. They require refinement, testing, and evaluation through simulation modeling studies.

This project's third task explored the application of HEC-PRM to seasonal operations, with known initial storage conditions and available forecast information regarding future inflows. The approach taken was to perform 47 HEC-PRM runs for the January-July operating period, with one run for each year of historical record. Each HEC-PRM run began with the actual January 1 initial reservoir storage levels for the system. Inflows for each 7-month analysis period were modified inflows, provided by NPD, reflecting January 1 snowpack and runoff forecast

information. These are substantially the same inflows used by NPD for simulation studies of operation during the January-July period. The results of these runs provide a range of "optimal" operations under different potential inflow conditions. As with the use of HEC-PRM for strategic operating rule studies, this information might complement existing simulation modeling studies for seasonal reservoir operations.

Similar work has also been performed for the Missouri River system (excluding seasonal operation analysis) using HEC-PRM (USACE, 1992 and 1994b). The Columbia River System differs in several significant regards from previous applications of HEC-PRM for the Missouri River system. The Columbia River system, represented with 14 storage reservoirs and several tributaries, is much larger and has a far more complex configuration than the main stem Missouri River system. The storage capabilities of the Columbia River System, with a ratio of available storage to mean annual outflow of about 0.33, are also much smaller than for the Missouri River system (with unusually large ratio of over 3.2). With this small amount of storage relative to inflow, the Columbia River System's seasonal operation tends to be more significant than its operation for over-year storage.

Conclusions

The results of this study lead to the following conclusions.

1. HEC-PRM results can be used to suggest enhancements to operating rules for the Columbia River System. The suggestions are inferred from HEC-PRM results from analysis of data displays and comparison with current operations represented by HYSSR results.

2. Potential modifications to current operating rules should be tested, refined, and evaluated using simulation tools. Testing, refining, and evaluating of operating rules based on HEC-PRM results through the use of simulation models (such as HYSSR) is important due to the specialized conditions required to apply a prescriptive model such as HEC-PRM. The HEC-PRM model uses a fairly simple representation of the system, a monthly time step, and requires that all system objectives be specified as convex linear functions. Results from this simplified representation can be extremely useful, but usually need to be refined. Also, HEC-PRM results are solved using the entire period of supplied hydrology (past and future) and therefore represent operating decisions based on perfect foresight. Obviously, a reservoir operator can never know future inflows with certainty, so simulation models are useful to develop descriptive operating rules (based on what an operator does know) to produce results that mimic the prescribed results.

3. The overall operation strategy suggested by HEC-PRM is similar to current operations represented by HYSSR results. Annual drawdown and refill of system-wide storage under HEC-PRM is very similar to HYSSR results for the 50-year period examined. HEC-PRM operations differ from those of HYSSR mostly in the allocation of total storage within the basin.

4. The most significant suggestions arising from HEC-PRM results are to draw down Grand Coulee less frequently and typically to make smaller drawdowns. This operation entails greater and more flexible operation of Arrow and Duncan. Suggestions for modifying operation of other reservoirs are much less dramatic.

5. HEC-PRM can be applied to seasonal operation problems on the Columbia River System. A simple approach was demonstrated using HEC-PRM to predict promising operational decisions based on historical inflow data updated to reflect current runoff forecast information. This current season forecast-modified inflow data is routinely prepared by NPD staff. The HEC-PRM results are explicitly based on economic concerns and may provide a useful "second opinion" on seasonal operating problems compared to current simulation (HYSSR) results.

6. Seasonal operating results for HEC-PRM for the current dry year (1994 forecast) are consistent with HEC-PRM operations during dry years during the 50-year analysis. This comparison tends to support the idea that HEC-PRM results are stable in their structure, not varying greatly with small changes in inputs.

7. Applying HEC-PRM to strategic and seasonal operating rule development and the screening of planning alternatives is feasible and provides insights and operation justification unavailable from traditional simulation modeling studies alone.

Chapter 1

Introduction

1.1 Summary

This report examines the applicability of using the Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) to develop of strategic and seasonal operating rules and updated monthly operation for the Columbia River System. The development of operating rules from prescriptive model results is a classical problem in the academic engineering literature (Young, 1967; Karamouz and Houck, 1992). Rule-making from prescriptive model results can have several purposes:

1. Efforts to create operating rules can test the reasonableness of a prescriptive model and identify the model's limitations.
2. Operating rules inferred from prescriptive model results can suggest a promising operation approach which might not have been considered previously.
3. Prescriptive model results give more rigorous economically-based support for operational alternatives and define the limit of total economic performance for a system.
4. Operating rules inferred from prescriptive model results provide a rigorous point of departure for more detailed simulation modeling studies of reservoir operation.

As mentioned above, the exercise of formulating operating rules from prescriptive model results is a two step process. The first step takes advantage of the many benefits gained from prescriptive model results and the second step uses a simulation model to test and refine the inferred operating rules. For previous HEC-PRM operating rule applications, simulation testing and refinement of inferred operating rules has been found to be essential, usually as a second phase in a rule-making study (USACE, 1994b). This report is the first phase in a rule-making study -- a proof of concept phase not requiring the resources and time required for simulation testing and refinement.

The development of suggestions for updated monthly operations of a reservoir system is a newer application of HEC-PRM, explored here for the first time. Ultimately, this might be a more significant application of HEC-PRM models. The approach taken here is adapted from the technique long applied to the use of simulation models for reservoir operations (Hirsch, 1978). There is much flexibility in the application of HEC-PRM to these closer-to-real-time problems. Again, the central role of simulation modeling should not be displaced by the addition of results from prescriptive models in operational decisions, but rather, the prescriptive results should be used to complement simulation results.

1.2 Description of River System

The Columbia River basin covers 259,000 square miles in Washington, Montana, Oregon, Idaho, Wyoming, Nevada, Utah, USA; and in British Columbia, Canada, as shown in Figure 1.1. The basin includes more than 250 reservoirs and 100 hydroelectric projects on the Columbia, Snake, Kootenai, Clearwater, and Pend Oreille Rivers and their tributaries. More than 120 of these projects comprise the coordinated Columbia River Reservoir System. The U.S. Army Corps of Engineers (Corps) and the U.S. Bureau of Reclamation (Reclamation) operate this coordinated system for power generation, flood control, anadromous fish protection, navigation, and irrigation. Other river uses include water supply, recreation, and fish and wildlife. The Bonneville Power Administration (Bonneville) sells the power produced.

A network model of the Columbia River System was developed in the earlier phases of this work. This phase modified the previous network model slightly. The revised network is shown in Figure 1.2.

1.3 Naming Convention

The following convention was used to name data files or presentations on the Columbia HEC-PRM work.

The name consists of three portions:

Location--Alternative--Variable Name

1. The *location* portion of the name consists of an abbreviation of the point of interest not exceeding four characters (detailed in the following table).

2. The *alternative* portion consists of a number from 1 to 9.

3. The *variable name* portion is either:

   STO for storage,
   FLO for flow, or
   REL for reservoir release.

For example, reference to storage results at Libby resulting from the Alternative 5 HEC-PRM run would be named LIBB5STO. Table 1.1 lists the abbreviations used for system nodes. Table 1.2 describes the different HEC-PRM alternatives run for the Columbia River System.

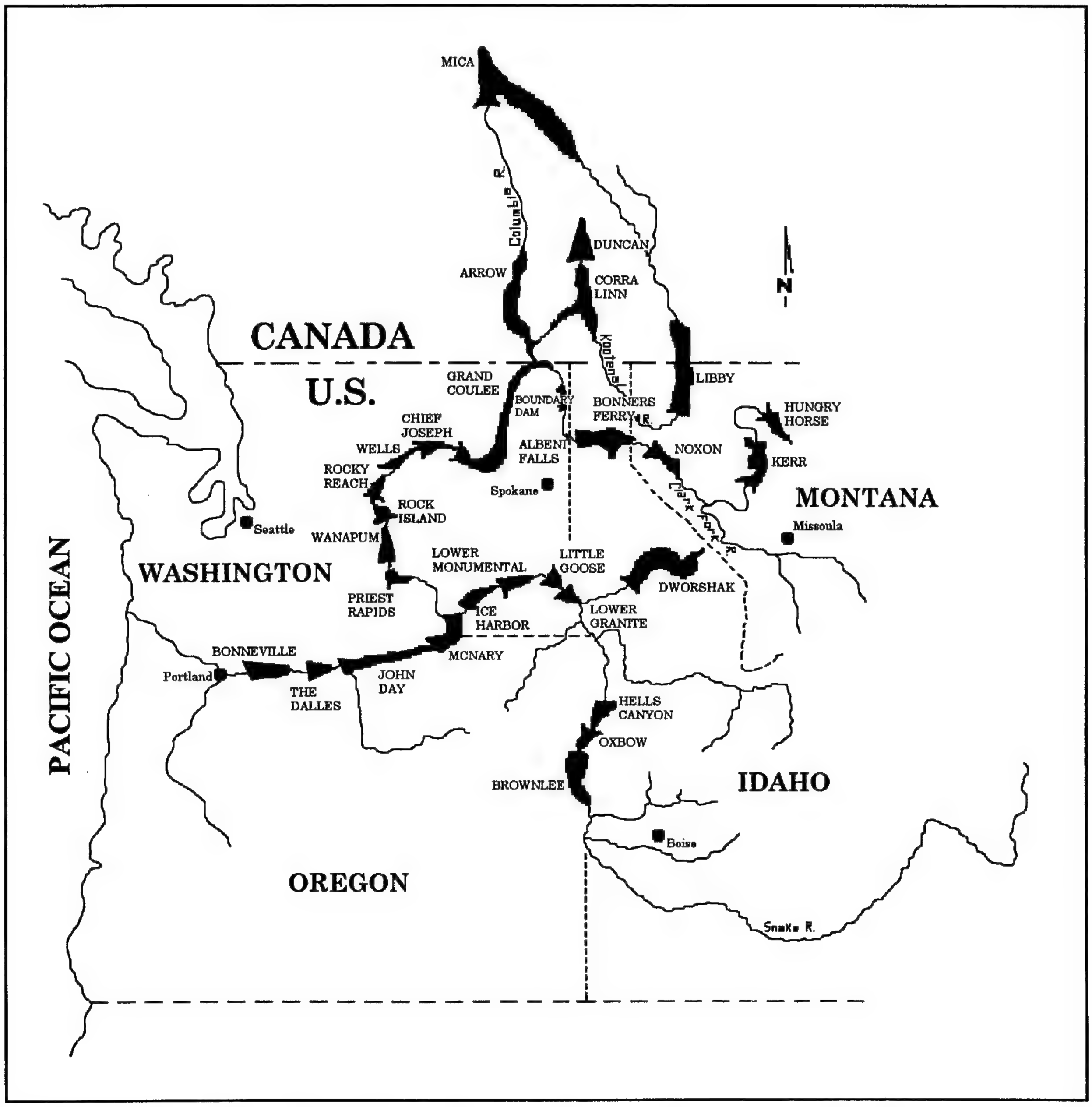


FIGURE 1.1 Columbia River System

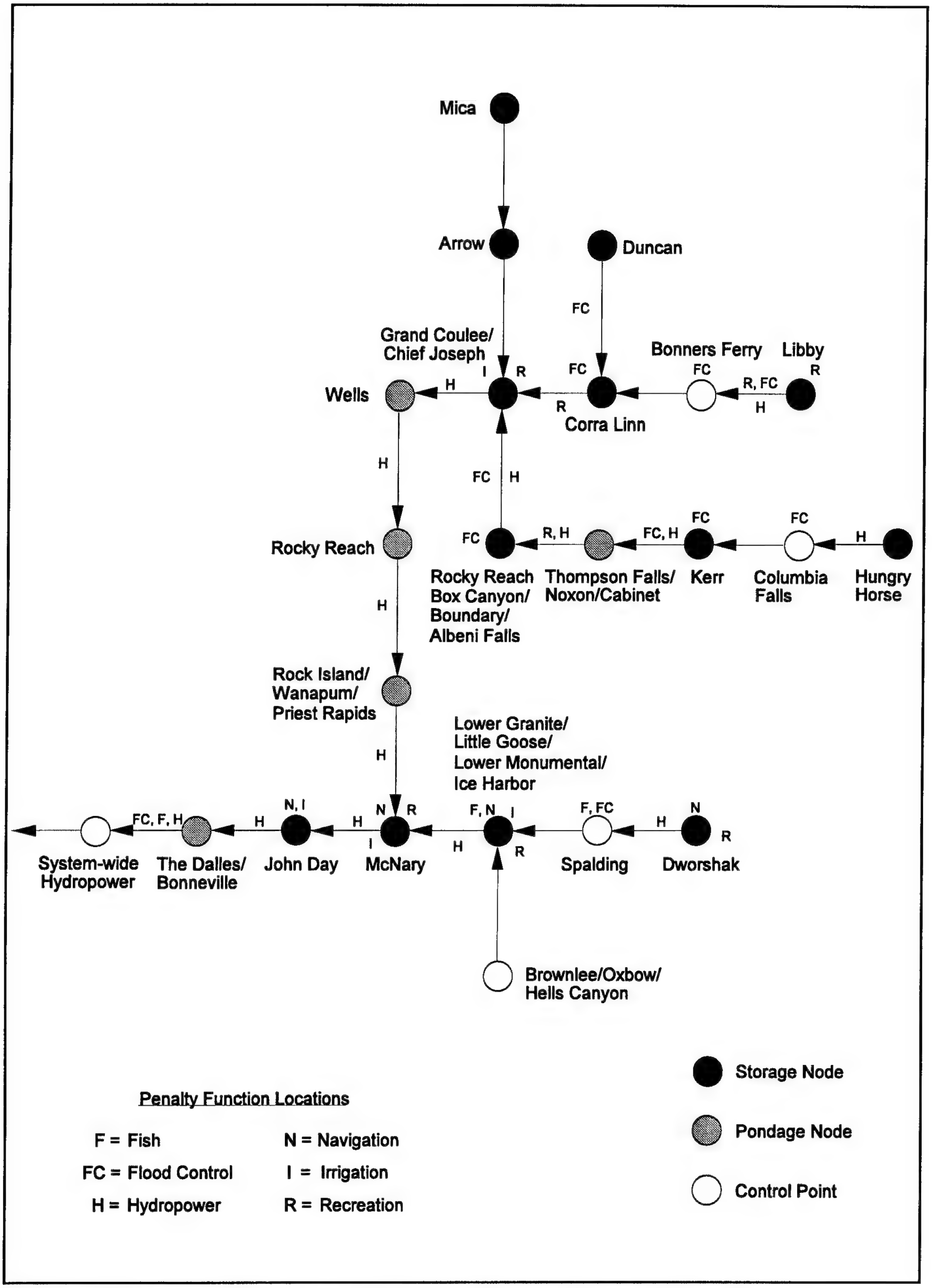


FIGURE 1.2 Updated Single-Period Network Model of Columbia River System

Table 1.1
Location Naming Convention

Abbreviation	Location Name	Node Type
MICA	Mica	Storage
ARRO	Arrow	Storage
DUNC	Duncan	Storage
CL	Corra Linn	Storage
LIBB	Libby	Storage
GC	Grand Coulee / Chief Joseph	Storage
ALBF	Albeni Falls / Rocky Reach / Box Canyon / Boundary	Storage
KERR	Kerr	Storage
HH	Hungry Horse	Storage
DWOR	Dworshak	Storage
BL	Brownlee / Oxbow / Hells Canyon	Inflow Node
GRAN	Lower Granite / Little Goose / Lower Monumental / Ice Harbor	Storage
MCNA	McNary	Storage
JDAY	John Day	Storage
DALL	The Dalles / Bonneville	Pondage
SPAL	Spalding	Control Point

Table 1.2
HEC-PRM Alternative Description

HEC-PRM Alternative	Description
0	Results as produced from NPD's simulation model (HYSSR)
1	Alternative 1 Model from Phase II (system is optimized for existing policy with existing Canadian Treaty)
2	Alternative 2 Model from Phase II (hydropower objectives are omitted) modified to include additional penalties on Mica, Libby, and the channel from Spalding to Granite
3	Alternative 3 Model from Phase II (additional storage is added at Mica Reservoir) modified to include additional penalties on Mica, Libby, and the channel from Spalding to Granite
4	Alternative 1 Model from Phase II modified to include additional penalties on Mica, Libby, and the channel from Spalding to Granite and Brownlee Reservoir is represented by HYSSR releases (operation of Brownlee is <u>not</u> determined by HEC-PRM)
5	Alternative 1 Model from Phase II modified to include additional penalties on Mica, Libby, and the channel from Spalding to Granite (operation of Brownlee is determined by HEC-PRM)
6	Alternative 4 with an additional node added (SYSHYDRO) to encourage "optimum" hydropower for the system. The penalties are based on "optimal" from NPD to maximize system-wide hydropower.
7	Same as Alternative 6 except for some corrections to the modified Mica Hydropower Penalties.
8	Seasonal Operating Rule Study

1.4 Organization of Report

The report is organized as follows. Chapter 2 reviews previous studies using HEC-PRM on the Columbia River System. Chapter 3 outlines modifications made as part of this work to the earlier Phase II HEC-PRM application to the Columbia River System. Chapter 4 presents the results of this improved HEC-PRM model. Chapter 5 compares these results to current operations, represented by HYSSR results, for 50 years of hydrology (1928-1978). Chapter 6 outlines a set of preliminary system operating rules which can be inferred from the improved HEC-PRM results and discusses some of their implications. Chapter 7 is a preliminary discussion and example of how HEC-PRM might be employed with forecast information to aid in updated monthly operations of Columbia River System reservoirs. Chapter 8 assembles some thoughts on further applications of HEC-PRM to the Columbia River System. Conclusions are presented in Chapter 9.

Appendix A lists references for work cited in this document. A more theoretical review of approaches for developing operation rules from HEC-PRM results appears in Appendix B. Detailed suggestions for further applications of HEC-PRM appear in Appendix C. Appendix D details modifications to the penalty functions used in the Phase II Columbia River System application of HEC-PRM. Appendix E presents some methodologies investigated for the annual operation application of HEC-PRM discussed in Chapter 6. Appendix F discusses the discrepancy of total water flow between the HYSSR output and the HEC-PRM output.

Chapter 2

HEC-PRM Studies of the Columbia River System

2.1 General

This application of HEC-PRM to the Columbia River System succeeds two previous phases of model development and application to this system. This chapter reviews these earlier HEC-PRM models used for the Columbia River System and discusses modifications made to these models for the present study.

2.2 Previous Columbia River System HEC-PRM Studies

HEC-PRM Program

The Hydrologic Engineering Center's Prescriptive Reservoir Model (HEC-PRM) takes user-specified value functions for system purposes, reservoir system flow and storage capacities, and inflow scenarios and produces a time-series of reservoir operation decisions that optimize system performance (USACE, 1991b, 1993). The model is based on network flow optimization, an approach which has seen several applications to reservoir system operations and planning problems (Yeh, 1982). Recent versions of HEC-PRM are enhanced beyond most network flow optimization models by the addition of an iterative algorithm for considering hydropower production. HEC-PRM also has been applied to the Missouri River system (USACE, 1991a, 1992).

Phase I Columbia River System HEC-PRM Model

The Phase I HEC-PRM application to the Columbia River System provided and tested an initial formulation of the Columbia River System as a network flow optimization problem (USACE, 1991b). The results of this initial application demonstrated the reasonableness of HEC-PRM results of the initial model, particularly in the representation of the system, system objectives, and the representation of hydropower. This initial HEC-PRM application to the Columbia River system represented hydropower purposes as economic penalties which varied solely with reservoir release or with storage, and identified the need for representation of Canadian storage, upgrading of HEC-PRM's documentation and user-interface, and improvement in penalty functions representing project purposes.

Phase II Columbia River System HEC-PRM Model

The Phase II application addressed many of the shortcomings identified in the Phase I model and provided a practical application of HEC-PRM for preliminary comparison of reservoir planning alternatives for the Columbia River System (USACE, 1993). Three alternatives were developed and compared: 1) including all current system operation objectives, 2) removing hydropower from system operating objectives, and 3) providing an additional 5 MAF of storage capacity in Mica reservoir. The model results estimated the economic value of additional Mica storage capability, as well as patterns of reservoir operations under the three scenarios. The Phase II HEC-PRM model demonstrated the applicability of HEC-PRM to the screening and preliminary analysis of planning alternatives.

Potential Applications Identified for the Columbia River System in Phase II

Previous applications of HEC-PRM have identified several potential uses of the model for the Columbia River System. These include:

- screening and preliminary evaluation of alternatives,
- development of promising preliminary reservoir operating rule strategies, and
- development of promising shorter-term operation strategies.

For each of these uses HEC-PRM results may provide insightful and rigorously derived operations as a point of departure for more detailed simulation studies.

This report presents the results of a preliminary investigation of the application of HEC-PRM to the development of operating rules and the development of shorter-term operating strategies. These results are preliminary, since they include no refinement and testing by simulation studies.

2.3 Modifications to Previous HEC-PRM Columbia River Applications

Changes to the Phase II HEC-PRM application to the Columbia River System are reviewed in this chapter. Details of the modified penalty functions appear in Appendix B. The Phase II HEC-PRM application is described in the Phase II report (USACE, 1993).

The Phase II penalty functions were modified to improve the representation of penalties on the Canadian projects, add additional fisheries penalties, more realistically represent Brownlee operations, and improve the representation of system-wide hydropower demands in the model application. The modified set of penalty functions are not a complete specification of water use values for the system, but do address gaps perceived in the Phase II model. These modifications were studied in various combinations as Alternatives 4-7 (Table 1.2). Alternative 7 was the model formulation used for most of the analysis presented in this report.

Canadian Project Penalty Functions

The Phase II HEC-PRM application contained few penalty functions on Canadian reservoir operations. Phase II Canadian penalty functions were generally of the "engineering" type, intended to keep reservoir operations within the general hydraulic design limits of the system. The following penalties were added explicitly to Canadian reservoirs:

- hydropower penalties for Mica Reservoir (combined with Revelstoke Reservoir), and
- recreation penalties for Libby Reservoir Storage.

Additional recreation penalty data are available for other Canadian locations (Mallette, 1993) but are small relative to other penalties on the system. Including them would require substantial modification of the Phase II network, which was beyond the resources available for this study.

Penalty functions for Corra Linn were not modified, and therefore retain operations according to the International Joint Commission agreement.

Additional hydropower penalties at Mica was especially desirable. It is a major hydropower facility with the potential for significant effects on the operation of Grand Coulee and other downstream reservoirs.

Additional Fisheries Penalties

From the Phase II study, additional fisheries penalties at Priest Rapids, Bonners Ferry, Spalding, Columbia Falls, and Hungry Horse storage were identified as desirable. Additional fisheries penalties were developed for Spalding in time for this study.

Brownlee Operations

Only hydropower penalties were present on Brownlee reservoir in the Phase II application. These seemed insufficient due to other uses on and directly downstream of Brownlee. It was found that the electric grid served different peak demands than other hydropower plants in the modeled system, and that this demand was not represented in the existing hydropower penalties for Brownlee. This, combined with the private ownership and operation of Brownlee, encouraged exploration of alternative means of handling Brownlee in the HEC-PRM application. After discussions with NPD staff, it was decided to represent Brownlee operations by replacing Brownlee reservoir in the application with Brownlee release data from HYSSR.

Hydropower Representation

Two significant deficiencies in hydropower representation were perceived in the Phase II application. First, the Phase II application had no representation of system wide hydropower demands. This caused a seasonal imbalance between hydropower production and demands in the Phase II results, even though annual production typically matched annual demand well. Second, in view of the wide operating range of releases from the major upstream storage projects and the

increased computational speed of HEC-PRM, it was felt that a finer piece-wise linearization of hydropower penalties was desirable for Libby, Hungry Horse, and Dworshak reservoirs.

The representation of system wide hydropower is limited in a network flow model. An additional seasonal penalty function on flow at The Dalles was therefore added to approximate total hydropower demand. In discussions with NPD staff, it was felt that, given the large run-of-river capacity of the system, this might adequately represent system wide demands. The derivation of a slope for this penalty function appears in Appendix D. More discussion of other options for representing system wide hydropower demands appears in Appendix C.

A finer resolution of hydropower penalties was examined for several upstream hydropower sites. Upon examination, it was decided that the existing penalty function discretization was adequate for this project.

Fish Flow and Flood Control Conflict at The Dalles

There is an apparent conflict in operations downstream of The Dalles between fish migration and flood control. Current penalties imply that optimal fish flows incur flooding penalties and vice versa. This conflict is partially an artifact of the use of regression to relate peak flood flows to average monthly flows and may also be due to uncertainty in estimating fish migration flows. This apparent conflict has not been entirely resolved, but its magnitude is small on the scale of basin operations.

2.4 Incidental Improvements to HEC-PRM

Several modifications were made to the HEC-PRM program while developing the latest HEC-PRM model for the Columbia River system (USACE, 1994a). The following improvements were made:

- option to add special end of analysis period penalties,
- ability to input time varying constraints,
- improved diagnostic capability for solver, and
- more user control of results output.

The end-of-analysis period penalty is particularly useful when applying HEC-PRM to annual or seasonal operations studies. This feature allows the user to set a target storage for the last period with a corresponding penalty if the target is not met. Previously, the storage for the last time step was constrained.

The ability to use time-varying constraints was added to allow for seasonal variations in upper or lower bounds in flow or storage. An example is if there is a significant amount of ice during winter months that reduces the maximum flow capacity in a waterway.

The additional runs of the HEC-PRM program for this study revealed occasional problems during solver execution. Modifications were made to make the solver more robust and additional code was added to help identify problems.

The default level of output for HEC-PRM results was changed to reduce the amount of information written to a HEC-DSS (USACE, 1990) file. This was done to reduce the amount of seldomly used information written to each output file. All information is still available, but the size of routine output files have been reduced significantly.

A methodology was developed to allow transfer of HEC-PRM results into a spreadsheet for further processing and analysis. Macros were developed within the spreadsheet used to greatly facilitate data manipulation and post processing. This option enhanced the methods used for interpretation of HEC-PRM results.

2.5 Summary

The development of the HEC-PRM model for the Columbia River system has gone through two phases prior to this study. The modified and expanded set of penalties developed for this study does not constitute a complete and final set of penalties for the system. Instead, this modified and expanded set of penalties attempts to address perceived deficiencies in the penalty functions used in the Phase II Columbia River system study. The further application of HEC-PRM to the Columbia River system has resulted in improvements to the overall model which make it easier to use for future studies on the Columbia and other systems.

Chapter 3

HEC-PRM Alternative 7 Results

3.1 Introduction

This chapter presents the results of the final HEC-PRM model (Alternative 7 described in Table 1.2) of the Columbia River System using 50-years of inflow hydrology (1928-1978). Results are presented for each reservoir in the system. They are then compared with current operating policy, using HYSSR results for the same inflow record to represent current operating practice in Chapter 4. The HEC-PRM results and their comparison with current operations form a basis for the operating rule strategy developed in Chapter 5. Some of these conclusions are presented in this chapter. Since this chapter contains more figures than text, figures are presented at the end of the chapter.

3.2 HEC-PRM Results

Presentation of HEC-PRM reservoir storage results is divided into sections focusing on the behavior of the system's three lowest reservoirs, three reservoirs with relatively constrained annual operations, and the remaining major storage projects. Results for flows at the Dalles are then presented, followed by a brief presentation of the distribution of system-wide storage throughout the year. These results are from HEC-PRM run Alternative 7.

John Day, McNary, and Granite Storage Results

John Day, McNary, and Granite reservoirs are currently operated almost as run-of-river projects. HEC-PRM results verify this general approach to operating these reservoirs. Figures 3.1, 3.2, and 3.3 show the range of storages for these reservoirs throughout the year. John Day operations (Figure 3.1) are almost always constant full pool. The most notable exception occurs during a few months of the 1930's drought, when drawdown reaches the maximum allowed by the model. Other minor short-duration drawdowns occur during flood years.

McNary operations (Figure 3.2) also vary only within a limited range, but more frequently. Draw-down to near the lowest level allowed by the model (1170 KAF) can occur in almost any month, except for July, when the reservoir always refills. Drawdown to about 1240 KAF is common in the spring (March and April). As illustrated by the exceedence probability plot in Figure 3.2, several specific storage levels are preferred by the model.

Under HEC-PRM operations, Granite (Figure 3.3) has a greater tendency to remain full than McNary, but less than John Day. Non-full conditions are rare between June and October. During other months, the reservoir can be drawn down to its lowest allowable levels, but this is rare. Only in January through April is drawdown to 1700 KAF common.

Albeni Falls, Kerr, and Corra Linn Storage Results

Albeni Falls, Kerr, and Corra Linn reservoirs are operated in accordance with fairly strict rule curves. In the case of Corra Linn, these rule curves correspond to an international agreement of the International Joint Commission. For these reservoirs, penalty functions reflecting stiff penalties for violating these rule curves were entered. The result is a regular annual drawdown-refill cycle. Figures 3.4, 3.5, and 3.6 show the range of storages for these reservoirs throughout the year.

Albeni Falls operation (Figure 3.4) is regular with some exceptions during flood years, when water is stored above the normal maximum pool. A few other irregularities in the pattern also are evident. Typical operation draws down the reservoir to its lowest allowable level early in the calendar year, keeps the reservoir empty until April when refill starts, and fills by July. The reservoir is typically kept full until January, but can be drawn down early, particularly during drought years.

Kerr operations (Figure 3.5) are qualitatively similar to Albeni Falls. The typical drawdown-refill cycle drains the reservoir to 572 KAF in early spring, refilling during late spring and summer, with slow releases during fall and winter months. Exceptions to this pattern, mostly more rapid drawdowns in the fall and winter, seem to accompany drought years.

Corra Linn operations (Figure 3.6) have a similar pattern. The reservoir is drawn down to its lowest allowable levels by March, with typical refill starting in April and being completed by September. Major irregularities occur due to over-filling above normal maximum storage levels during flood events.

Major Storage Reservoir Results

The major storage reservoirs include Mica (with 7 MAF of storage available in the model), Arrow (7.1 MAF of storage), Duncan (1.4 MAF), Libby (5 MAF), Hungry Horse (3.1 MAF), Grand Coulee (5.2 MAF), and Dworshak (2 MAF). These reservoirs (except Grand Coulee) exhibit similar annual drawdown-refill cycles. The tendency is to fill by the end of July, with slow drawdowns during the fall and early winter, more rapid drawdown to minimum levels during the spring, and relatively rapid refill during the later spring and early summer.

Mica operations (Figure 3.7) are fairly regular, refilling completely in 80% of the years modeled. Failure to refill completely is common for drought years, although some refill occurs in all years. During some flood years, the reservoir may not draw down completely. Complete drawdown occurs in only 56% of the years. One major change from the Columbia River Phase II HEC-PRM model was the addition of hydropower penalties to Mica Reservoir representing hydropower generation at both Mica and Revelstoke reservoirs. The effect of adding these hydropower penalties on Mica operations is shown in Figure 3.8, which compares the Phase II's Alternative 1 Mica operations with the newer HEC-PRM Alternative 7 operation for median, 25% and 75% quartiles. The results with hydropower penalties tend to keep Mica fuller, with more rapid refill and less drawdown during the fall. These are not surprising results.

Arrow operations (Figure 3.9), with slightly more storage and no hydropower penalties, offer a more dramatic drawdown refill pattern. Refill occurs in most years by July with fairly steady drawdown until January, when the rate of drawdown slows until the reservoir is emptied for March and April, with rapid refilling between April and July. Having no value placed on storage in Arrow, aside from storing water for downstream uses, Arrow may remain empty during some drought years and does not refill during dry years. The rates of drawdown are often less during flood years. Unlike most reservoirs in the system, Arrow spends over 30% of the time nearly empty.

Duncan operations (Figure 3.10) are of a character similar to Arrow's. Duncan is usually emptied by January and refills beginning in May, with refill usually complete by July, and relatively rapid drawdown between August and January. Exceptions to this pattern are years of only slight refill during drought and slower rates of drawdown during flood years. Like Arrow, Duncan also has no hydropower penalties. Thus, both Duncan and Arrow tend to function as "free" storage for downstream hydropower reservoirs. Duncan is essentially empty almost 40% of the months studied and full only a little over 20% of the time.

Libby is a major high-elevation storage reservoir with hydropower production, much like Mica only with less storage capacity. Libby has a higher ratio of mean local inflows to active storage (0.62) compared to Mica (0.47), making Libby more attractive for over-year storage of water. Operation of Libby (Figure 3.11) is somewhat similar to Mica. Drawdown is complete 16% of the years, sometimes during droughts and sometimes in preparation for flood control operations. Typical drawdown levels vary greatly from year to year, with rare years having only a few 100 KAF of drawdown (1963). Refill occurs almost completely by July of all years, with slow drawdown during fall and early winter and more rapid drawdown before low storage levels in April. Libby is empty only for short periods.

Hungry Horse is the highest elevation reservoir with significant storage capacity. While having a distinct drawdown-refill cycle (Figure 3.12), Hungry Horse is completely drawn down only during 4% of the years, only during extreme drought years. During these drought years, Hungry Horse does not refill for several years. (Hungry Horse's ratio of active storage to mean annual inflow is 1.26.) Complete refill of Hungry Horse occurs in over 80% of the years. Typical Hungry Horse operation is to refill in July, with steady drawdown through December, slower drawdown to a low of about 2 MAF in March or April, followed by refill.

Grand Coulee operation (Figure 3.13) is almost as a run-of-river reservoir, with occasionally significant drawdown early in the year to create several million acre-ft of storage for spring runoff. Grand Coulee is drawn down to its lowest allowed level in only 18% of the years. No significant drawdown of Grand Coulee occurs in 32% of the years studied. When Grand Coulee drawdown occurs, it usually begins in March and ends in April, with refill always occurring by June. HEC-PRM operations keep Grand Coulee full in more than 85% of the months studied. Grand Coulee's storage capacity to average annual inflow ratio of 0.07 would seem to classify this reservoir as a near run-of-river facility.

On the southern side of the Columbia River system, Dworshak and Brownlee reservoirs regulate flow in the lower Snake River Basin. For this study Brownlee operations were replaced with HYSSR results, as discussed in Chapter 2. Dworshak operations (Figure 3.14) have a similar drawdown-refill cycle to the other major reservoirs on the system. Drawdown is usually complete and refill is typical, but not always assured. Refill occurs between April and June, with typically steady drawdowns between July and March. Complete drawdown occurs in only a little over half the years.

Flows at The Dalles

Flows at The Dalles under HEC-PRM operations are highly cyclical (Figure 3.15). The monthly quartile and time series plots on Figure 3.15 show very regular flows during the months between September and February of about 8,500 KAF/month. This amount dips substantially during drought years 1929-32, 1943-44, and 1977 by a few 1,000 KAF/month. While flows during other times of the year are greater, their distribution varies greatly with the particular year's inflow hydrology. For instance, during drought years, relatively little outflow is available during any month. During flood years, large outflow peaks are observed. This is required due to the relatively small amount of over-year storage available in the system.

As discussed in Chapter 2, a significant seasonally-varying penalty on Dalles outflow was added for the Alternative 7 HEC-PRM model. This penalty represented a demand to meet system-wide hydropower production targets. The effects of imposing these penalties are illustrated on Figure 3.16. A plot of the minimum and 25% quartile Dalles flows for Phase II Alternative 1 and current Alternative 7 HEC-PRM results along with the flow at which the penalty was assessed. The system-wide hydropower penalties boosted winter and spring flows only during dry years. Flows for the 25th percentile are almost identical for the two runs.

Total System Storage

Total system storage for HEC-PRM results has a pattern similar to current operations, as discussed in a later section. The system as a whole has a significant annual drawdown-refill cycle. System storage typically peaks in July, with greatest drawdown typically in March or April. Table 3.1 shows quartile values for total system storage for each month of the year.

Estimates of over-year drought storage, typical within-year storage, and flood storage can be gleaned from these statistics. If the median numbers reflect the typical year's drawdown-refill cycle, the difference between the monthly median maximum (62.0 MAF in July) and minimum (36.7 MAF in April) should be the typical within-year storage amount, about 25.3 MAF. Over-year drought storage for the system can be estimated by subtracting the minimum value for total storage seen during the 50-year analysis (27.9 MAF in April) from the median monthly minimum (36.7 MAF in April), for a drought storage value of 8.8 MAF. Flood storage in the system (ignoring operation of normal storage pools for flood control conditions) can be estimated by subtracting the maximum value of system-wide storage (64.8 MAF in August) from the median monthly maximum (62.0 in July), for a flood control volume of 2.8 MAF.

Table 3.1
Total System Storage Quartile Values

	Storage Quartile Value (MAF)				
Month	**Minimum**	**25%**	**Median**	**75%**	**Maximum**
January	31.0	41.9	44.6	46.5	51.2
February	27.2	39.2	41.4	43.3	49.0
March	28.1	34.5	37.1	39.7	43.9
April	27.9	33.1	36.7	39.5	46.2
May	35.6	42.0	45.6	49.0	57.0
June	47.0	54.8	58.0	60.0	62.3
July	47.2	61.3	62.0	62.2	64.2
August	46.5	58.3	60.2	61.7	64.8
September	44.7	55.9	57.5	59.2	63.7
October	41.1	51.9	54.1	56.3	61.8
November	39.4	49.7	51.1	52.9	58.7
December	35.6	46.7	48.6	50.9	56.8

Distribution of System Storage

While the behavior of total system storage is interesting, the distribution of storage within the Columbia River System can be more important. This section describes the allocation of total system storage among the system's reservoirs. Figures 3.17 through 3.21 show the allocation of system and sub-system storage among different reservoir sub-systems and individual reservoirs. There are definite trends in the allocation of system to sub-systems of reservoirs and the allocation of sub-system storage to individual reservoirs. Priorities in draw-down and refill are evident, with some reservoirs being partially or completely drawn down before others.

Figure 3.17 shows the allocation of total system storage among different branches of the Columbia River System. When filling or drawing down from extremely full (extreme flood) conditions, the last full and first-emptied storage is in the Hungry-Horse-Kerr-Albeni Falls branch and the Libby-Duncan-Corra Linn branch. As discussed later, this storage is over-filling Albeni Falls and Corra Linn above the normal full storage levels. As the system draws down below about 63 MAF, more water is taken from storage in the Hungry Horse-Kerr-Albeni Falls and Mica-Arrow-Grand Coulee branches, with the Mica-Arrow-Grand Coulee branch being

depleted much more rapidly. This pattern of draw-down continues until total system storage is reduced to about 48 MAF.

Below total system storage of about 48 MAF, withdrawal rates from the Mica-Arrow-Grand Coulee system are reduced (but not eliminated), while drawdown rates for the other system branches increase. The drawdown rate for the Snake and Lower Columbia branch (Dworshak, Brownlee, Granite, McNary, and John Day) is the slightest, and remains slight until system storage reaches its lowest levels. Drawdown rates for the Hungry Horse-Kerr-Albeni Falls and Libby-Duncan-Corra Linn branches increase, and continue at about the same rate until total system storage is reduced to approximately 37 MAF, where these drawdown rates are reduced. Below total system storage levels of about 37 MAF, drawdown is increased from the Mica-Arrow-Grand Coulee branch, mostly from Grand Coulee. The reverse of this storage allocation pattern appears to hold for system refill.

Similar examination of storage allocation can be made within each branch of the Columbia River System. Figure 3.18 shows the allocation of total storage in the Mica-Arrow-Grand Coulee branch of the system. Here, a more distinct pattern emerges. For storage levels between about 33 MAF and 37 MAF in the branch, drawdown is from some combination of Mica and Arrow; in some years it is mostly Mica and other years mostly Arrow. This probably depends on local inflows. Below 33 MAF of branch storage, drawdown tends to be mostly from Arrow, with some from Mica. When branch storage is reduced to about 26 MAF, Arrow is usually almost empty and almost all branch storage drawdown is from Mica, until branch storage is reduced to about 23 MAF. Below 23 MAF of branch storage, available storage in both Mica and Arrow is essentially empty, and further storage depletion must be from Grand Coulee. The reverse of this pattern appears to hold for refill of branch storage.

Figure 3.19 provides a similar illustration of storage allocation on the Libby-Duncan-Corra Linn branch of the system. The first drawdown from above normal full conditions is to reduce overfilling of Corra Linn, until branch storage is about 8 MAF. Withdrawal below about 8 MAF comes from drawdown of either Libby or Duncan, with a slightly greater tendency to draw down first from Libby. With total branch storage between about 8 MAF and 6 MAF Duncan is typically drawn down to empty. Between about 6.5 MAF and 4 MAF of total branch storage, Corra Linn is also drawn down, along with significant drawdown of Libby. Branch storage levels below about 3.5 MAF come almost entirely from drawdown of Libby.

The Hungry Horse-Kerr-Albeni Falls branch of the system has a similar draw-down pattern (Figure 3.20). Above-normal flood storage levels are first reduced by eliminating over-filling of Albeni Falls, until a normal full condition is achieved at about 7.5 MAF of total branch storage. Between about 7.5 MAF and about 5.5 MAF Hungry Horse contributes the greatest drawdown with some drawdown of Kerr. Between 4 MAF and 5 MAF, Albeni Falls is rapidly drawn down, along with some additional Kerr drawdown, and relatively steady levels of Hungry Horse storage. For branch storage levels below about 3.5 MAF, drawdown is almost completely from Hungry Horse.

For the Snake and Lower Columbia River branch of the system (Figure 3.21), drawdown of storage in this part of the system comes initially from Dworshak, with frequent contributions from Brownlee (from HYSSR results used in this analysis). With branch storage levels below about 9.5 MAF, some drawdown of Granite and more frequent drawdown of McNary appears, but most of the drawdown still derives from drawdown of Dworshak. Total branch storage levels below about 8.5 MAF typically have depleted Dworshak storage, with most of the remaining drawdown coming from Brownlee. John Day, Granite, and McNary all exhibit rather steady operations.

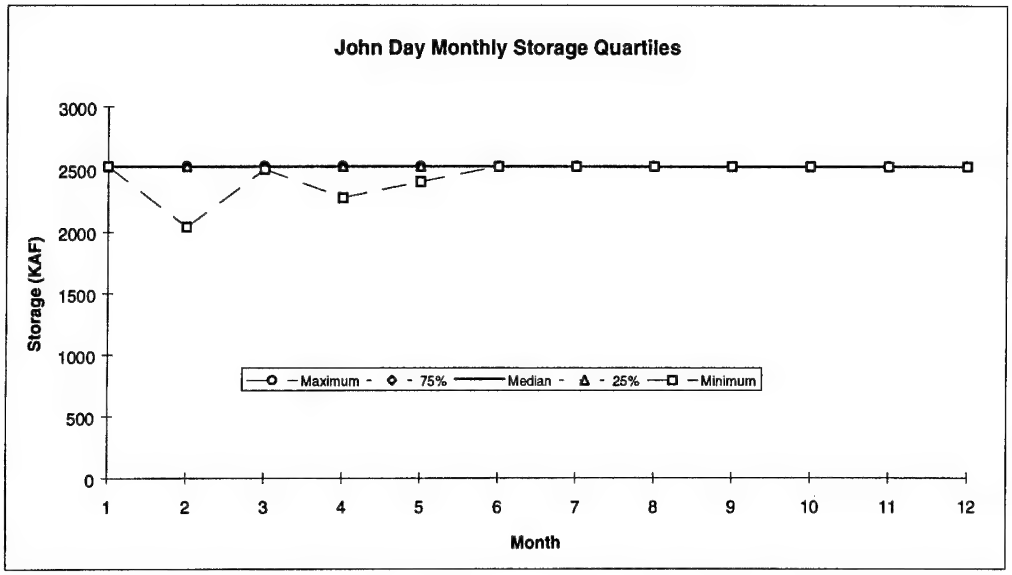
3.3 Summary

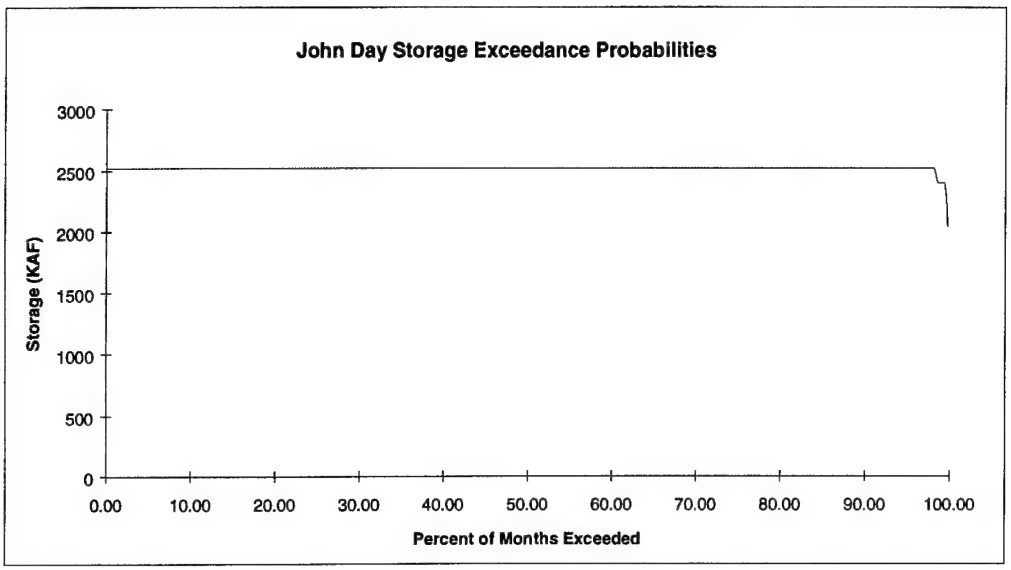
Given the relatively small amount of storage available on the Columbia River System relative to system-wide inflows, operations vary greatly by season and between wet and dry years. Like many hydropower systems, there seems to be a tendency to keep lower reservoirs full, operating essentially as run-of-river plants with maximal hydropower head. This operating pattern appears to apply to John Day, McNary, and Granite reservoirs. The tendency also applies to Grand Coulee, with the exception of occasional drawdowns during drought years and in anticipation of floods.

A middle tier of reservoirs consisting of Albeni Falls, Kerr, and Corra Linn, are constrained to highly seasonal, but very regular operations. These regular operations are interrupted mostly by occasional flood inflows which exceed outlet capacities. During droughts, more rapid draw-down of these reservoirs help to keep Grand Coulee full while maintaining flows at The Dalles.

For HEC-PRM operations, the large storage reservoirs on the system are located in the upper reaches of the tributaries, Mica, Arrow, Duncan, Libby, Hungry Horse, and Dworshak. Where reservoir storage relative to average annual inflows are smaller, the seasonal variation is minor, except for incomplete refill (during drought years) and drawdown (during wet years). Arrow and Duncan, lacking hydropower facilities, act as "free" storage to keep lower reservoirs, particularly Grand Coulee, operating at peak hydropower heads, and may experience very little refill during drought years.

Libby, Hungry Horse, and Dworshak, particularly large reservoirs on relatively smaller tributaries, tend to maintain the largest amount of over-year storage. These reservoirs experience their most extreme drawdowns during drought years and frequently do not refill during these years. They may also be drawn down to extremes in anticipation of flood events.





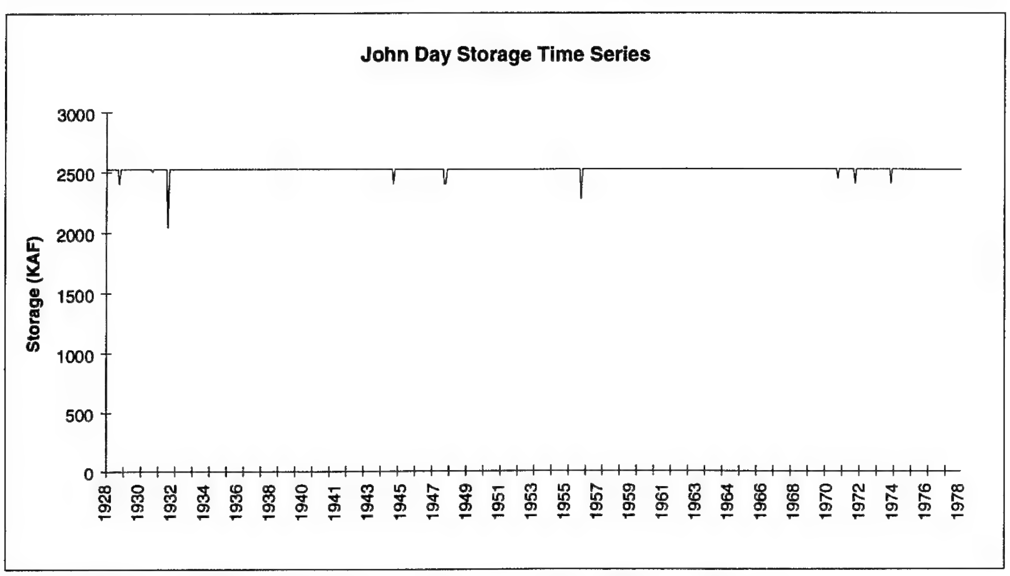
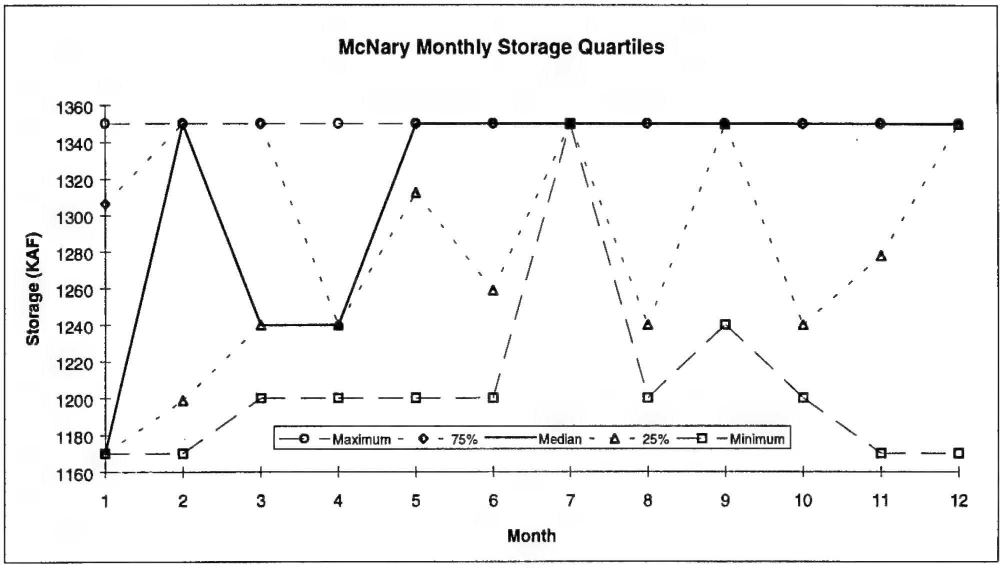
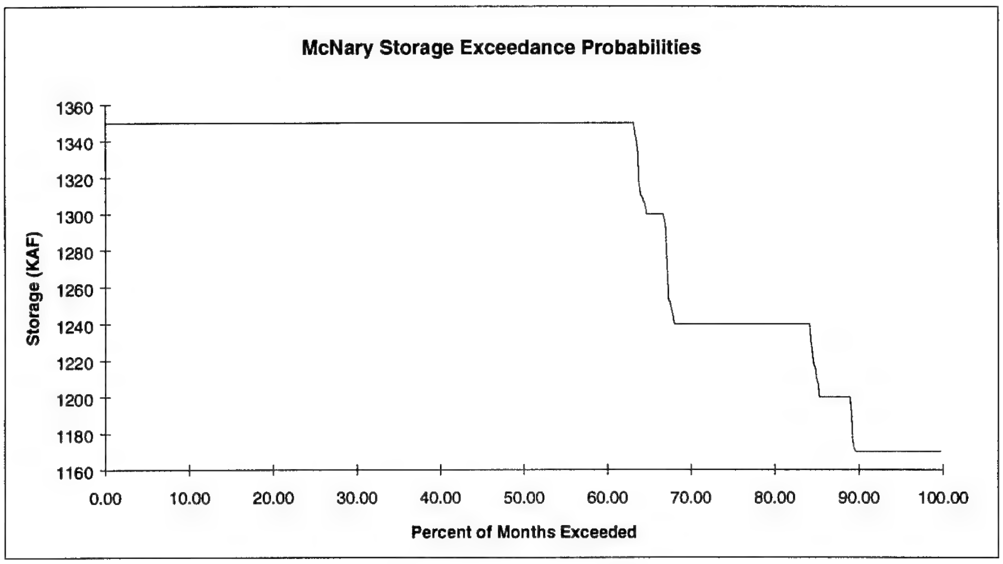


FIGURE 3.1 John Day Storage Results for Alternative 7





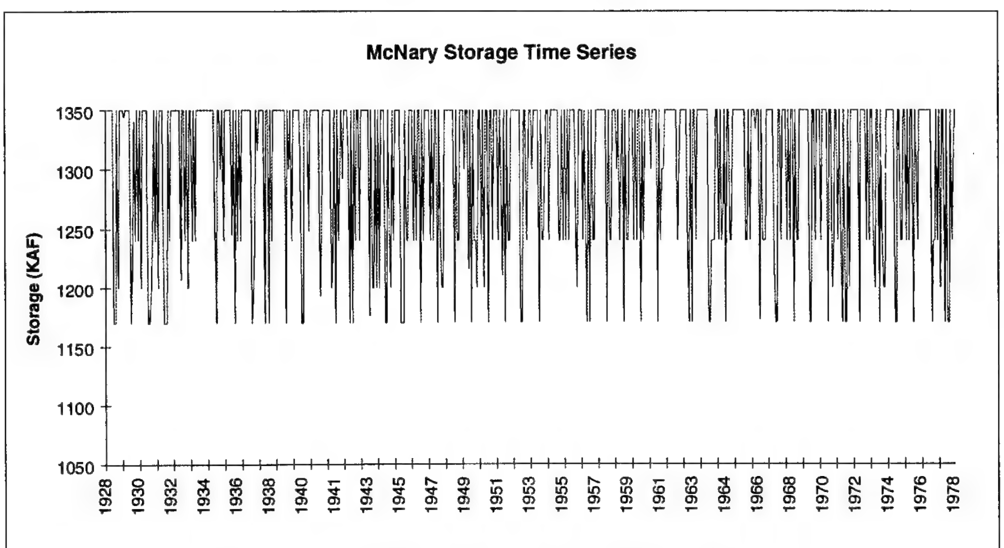


FIGURE 3.2 McNary Storage Results for Alternative 7

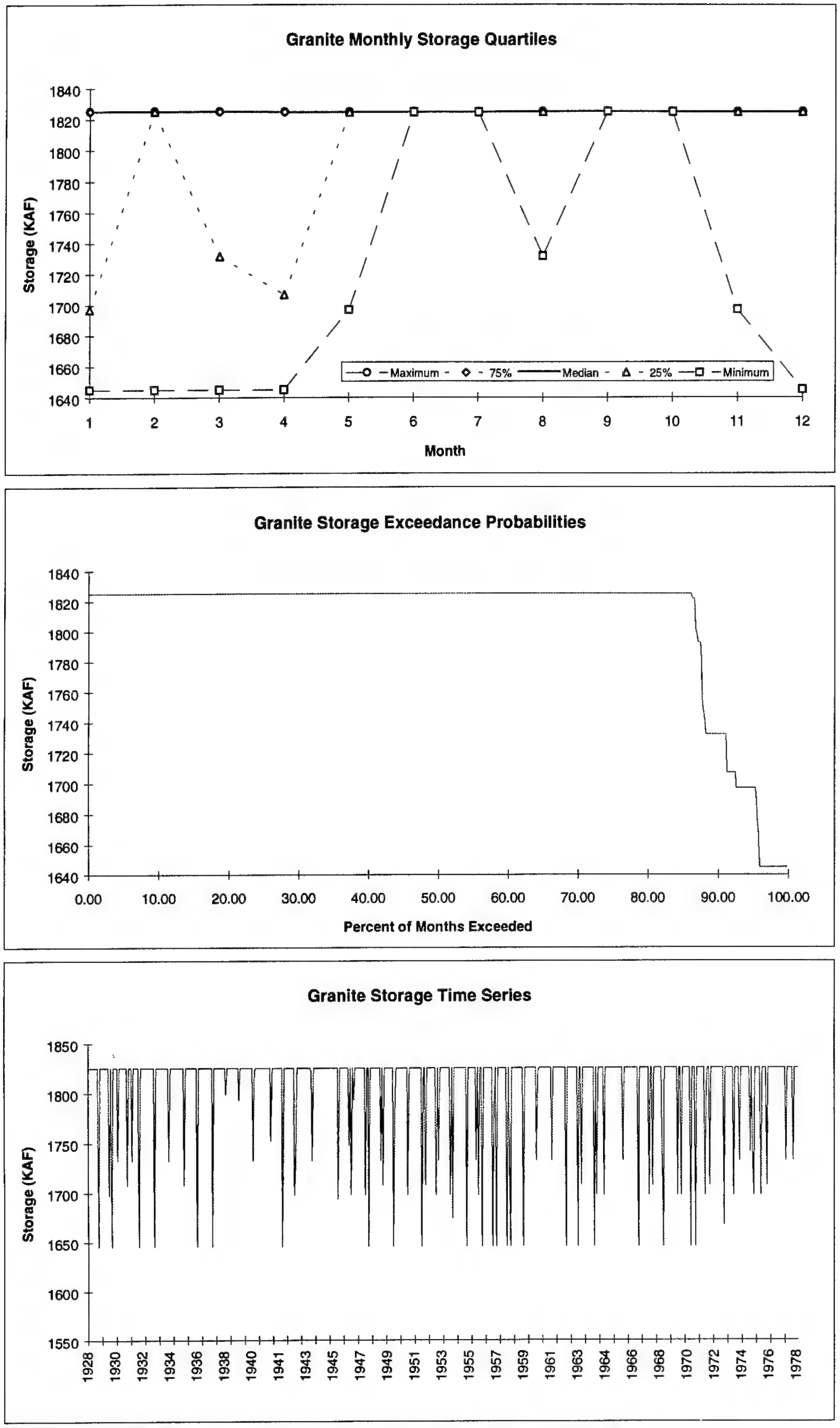
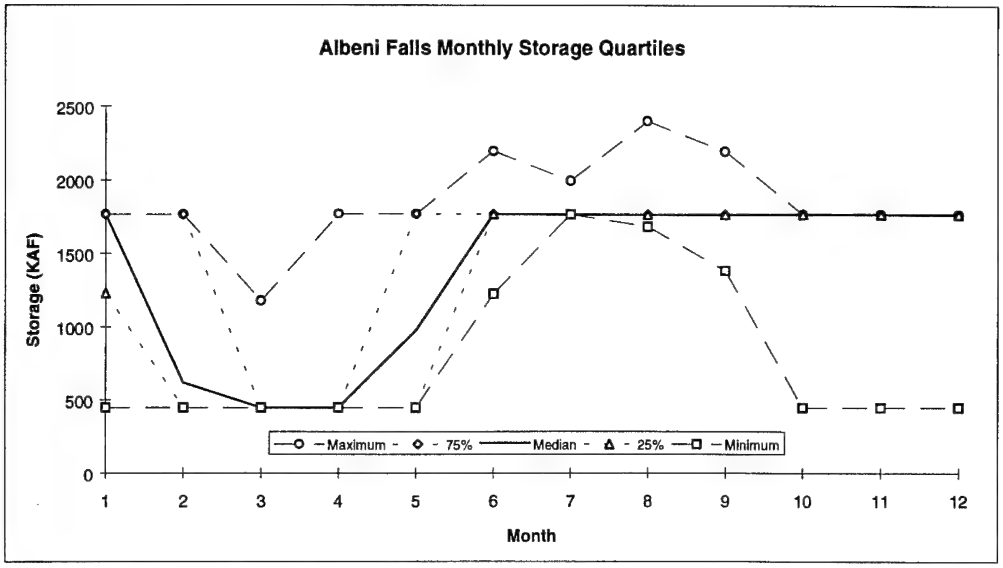
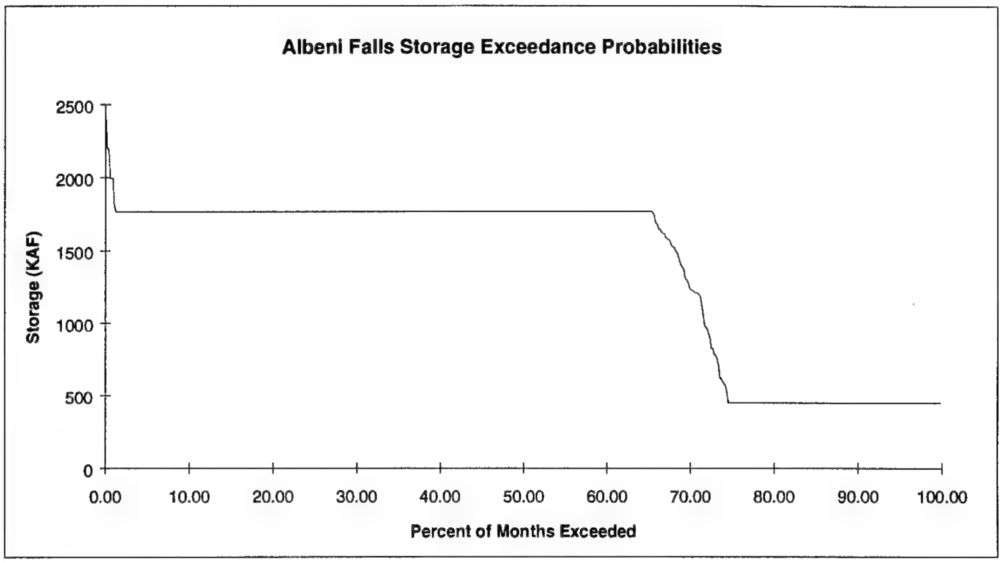


FIGURE 3.3 Granite Storage Results for Alternative 7





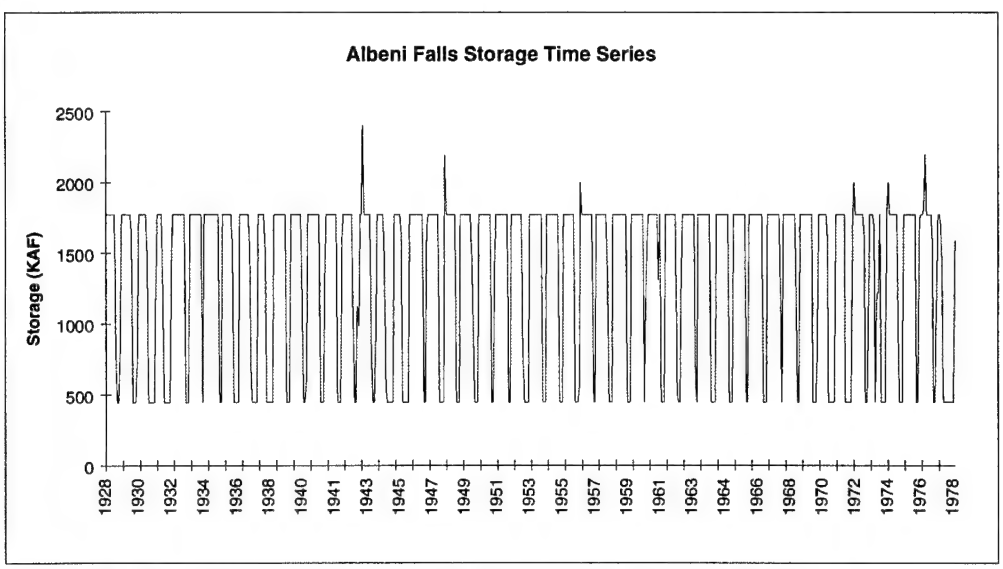
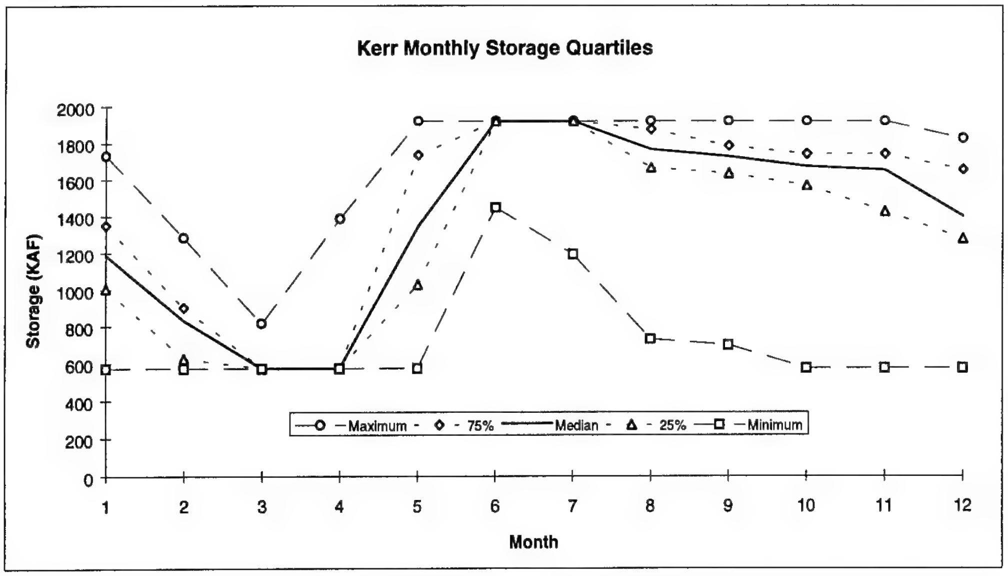
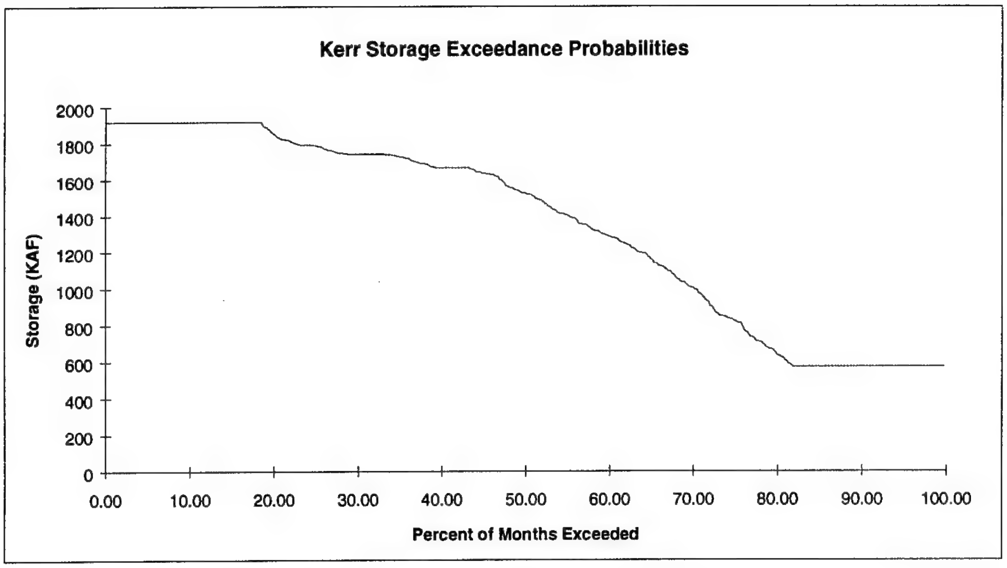


FIGURE 3.4 Albeni Falls Storage Results for Alternative 7





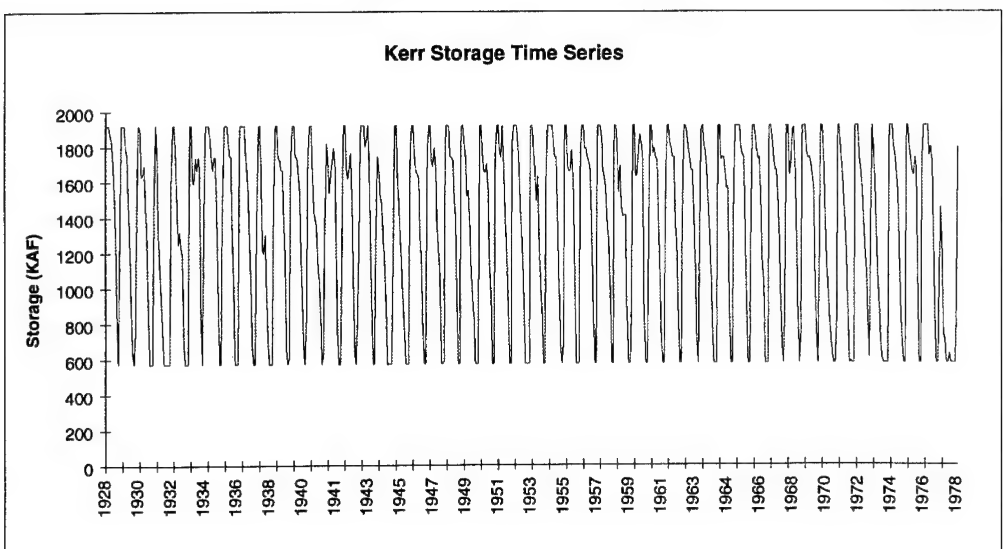
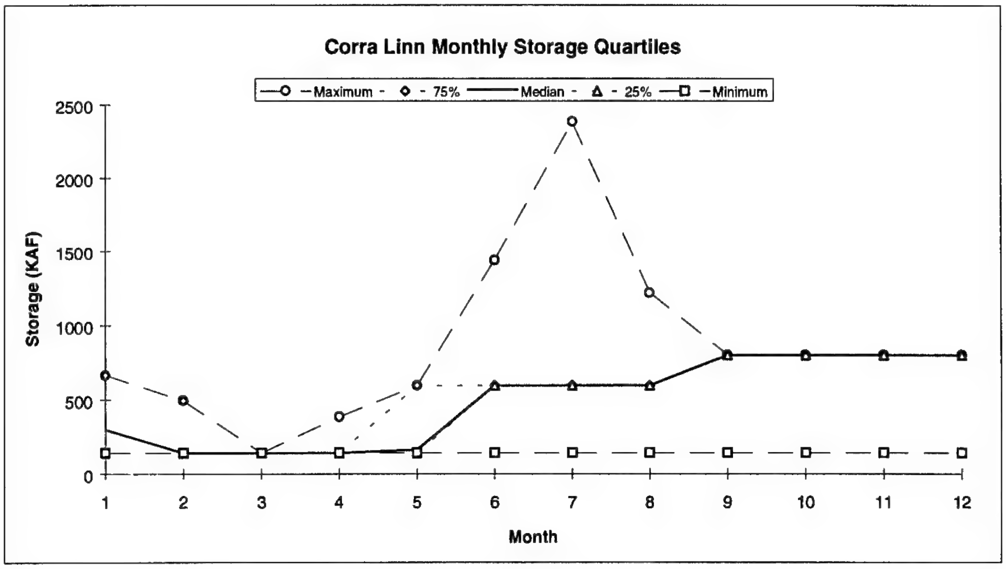
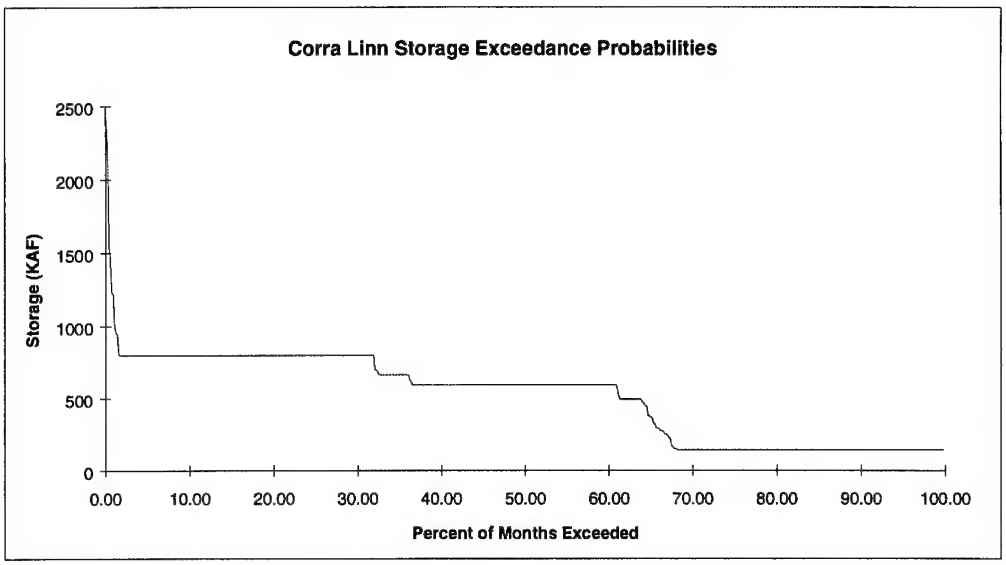


FIGURE 3.5 Kerr Storage Results for Alternative 7





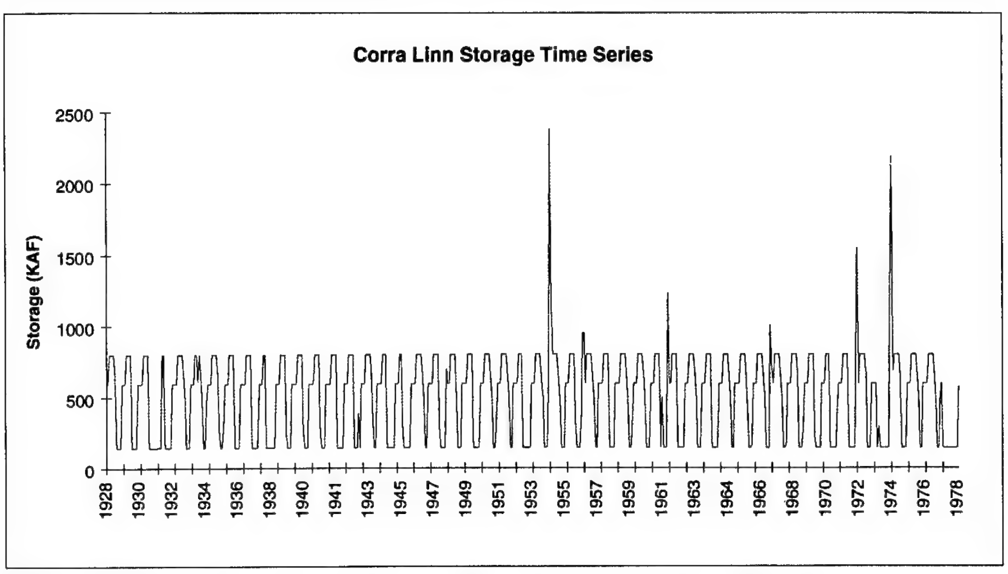


FIGURE 3.6 Corra Linn Storage Results for Alternative 7

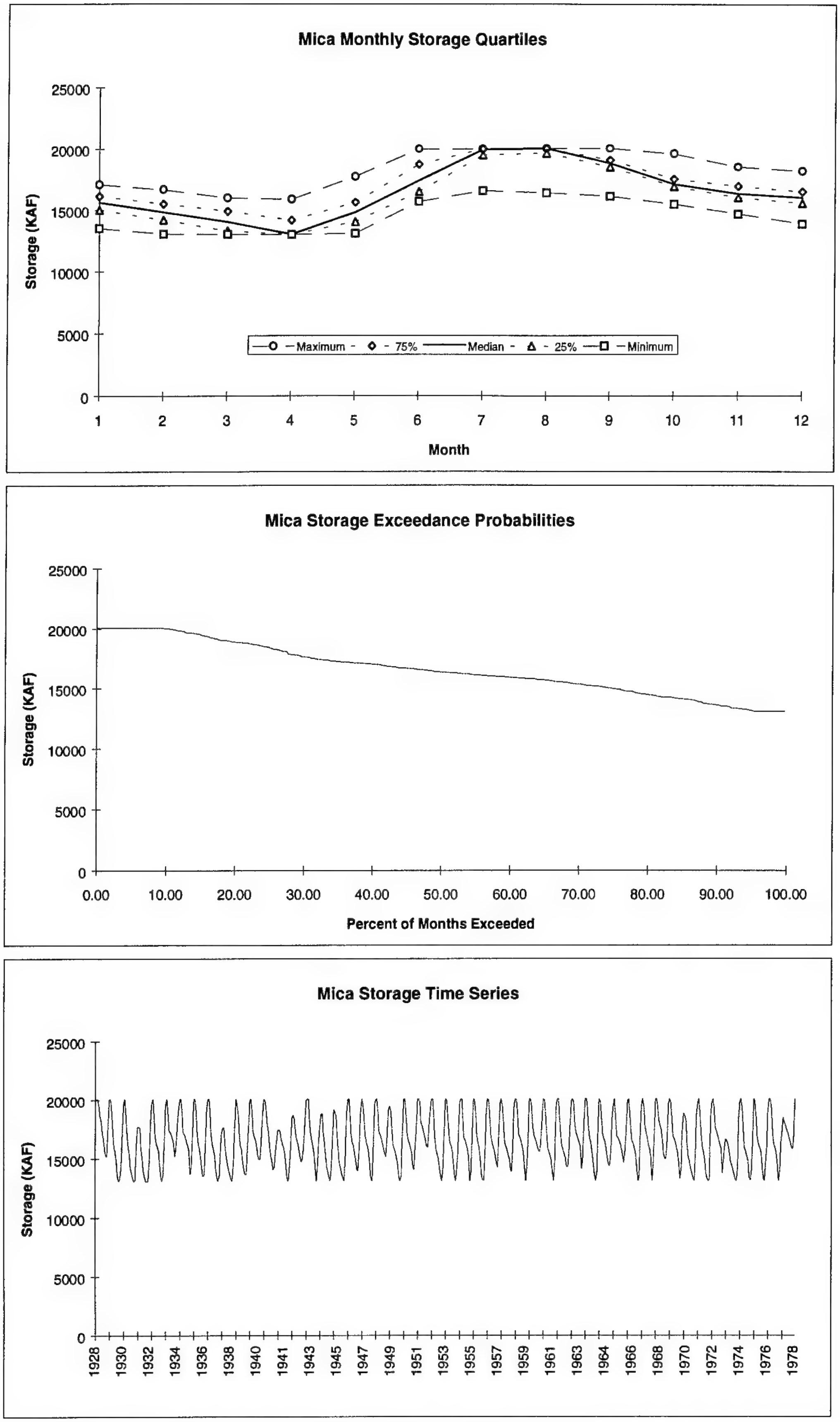


FIGURE 3.7 Mica Storage Results for Alternative 7

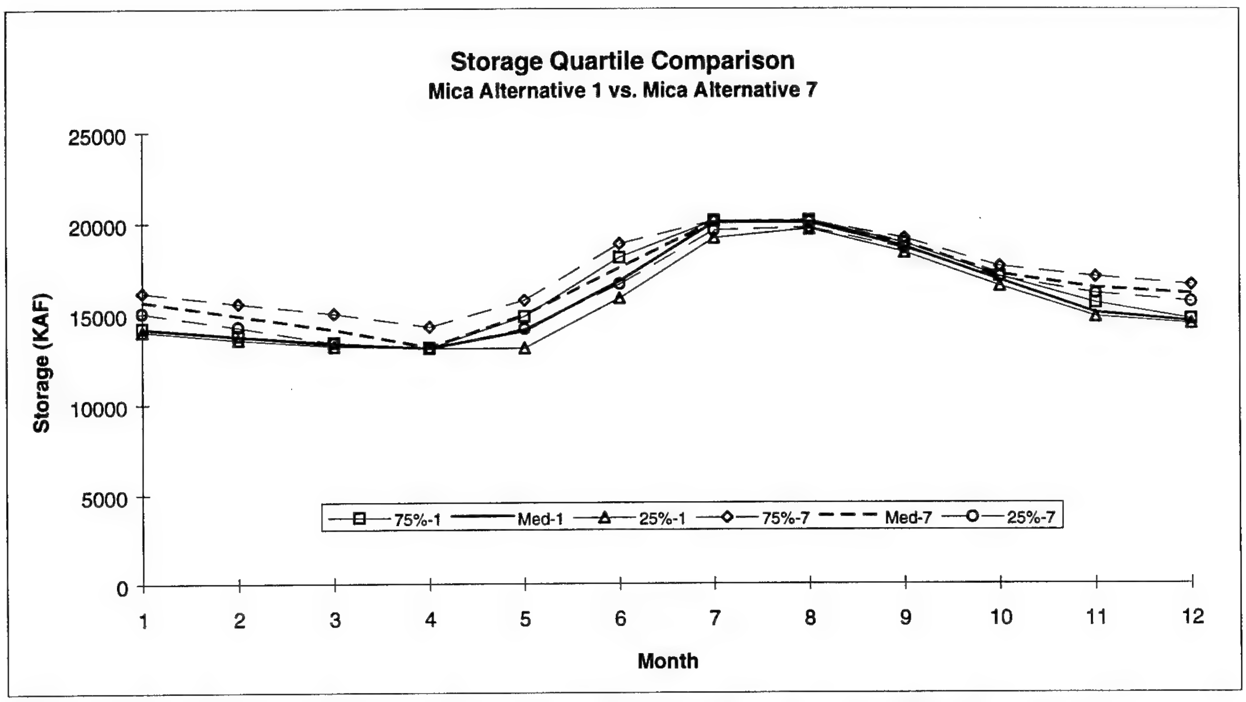


FIGURE 3.8 Effects of Adding Hydropower Penalty Function to Mica Reservoir

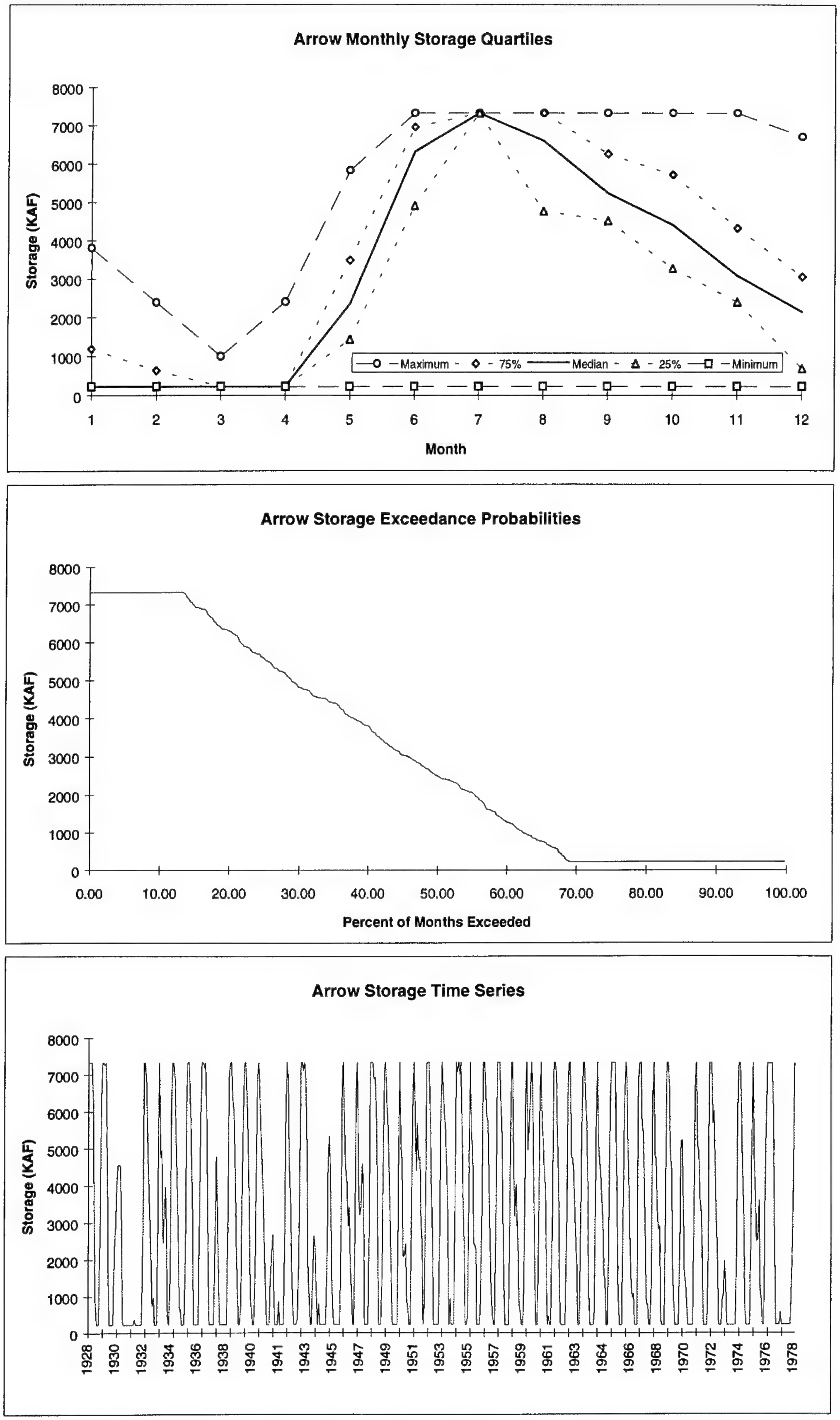


FIGURE 3.9 Arrow Storage Results for Alternative 7

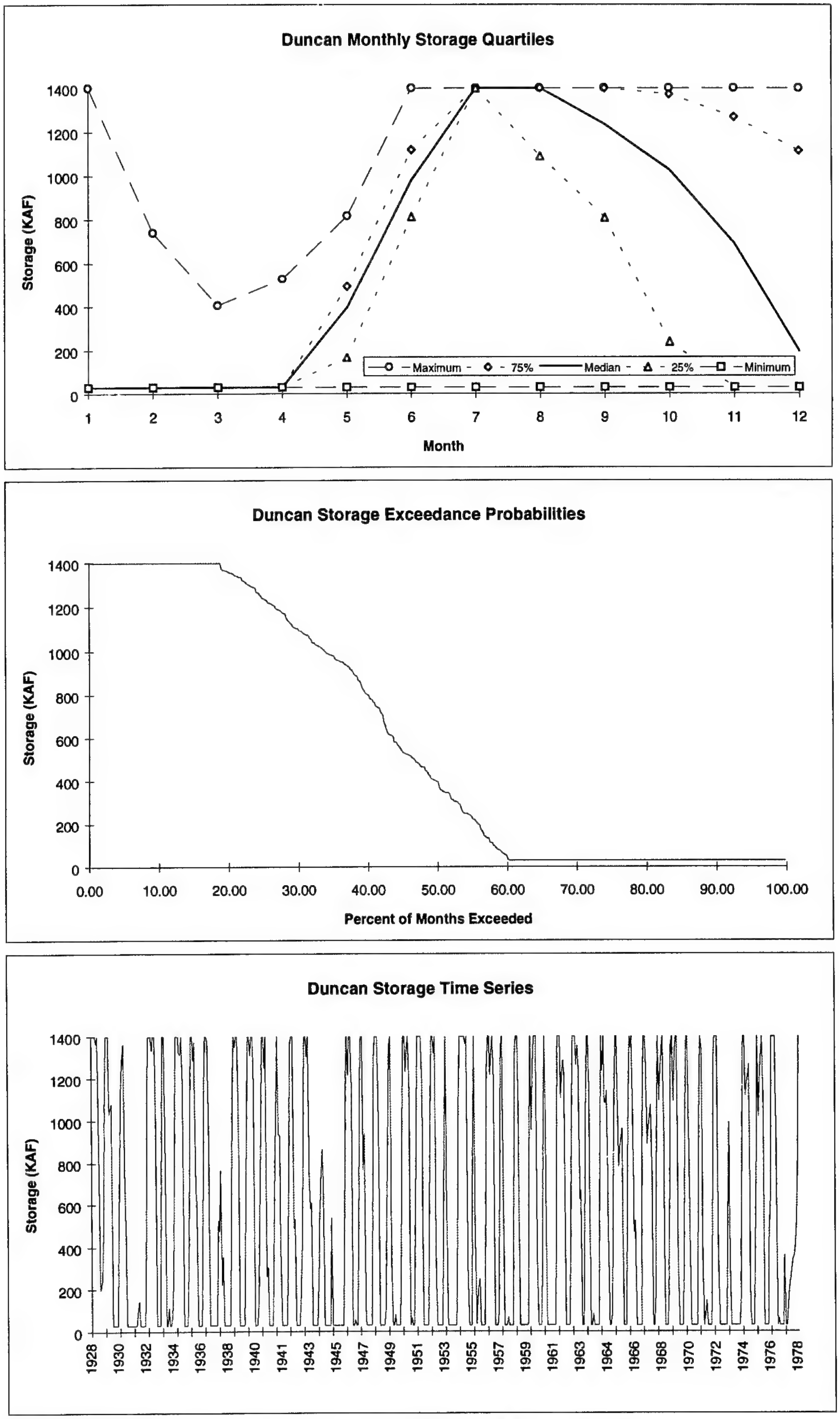


FIGURE 3.10 Duncan Storage Results for Alternative 7

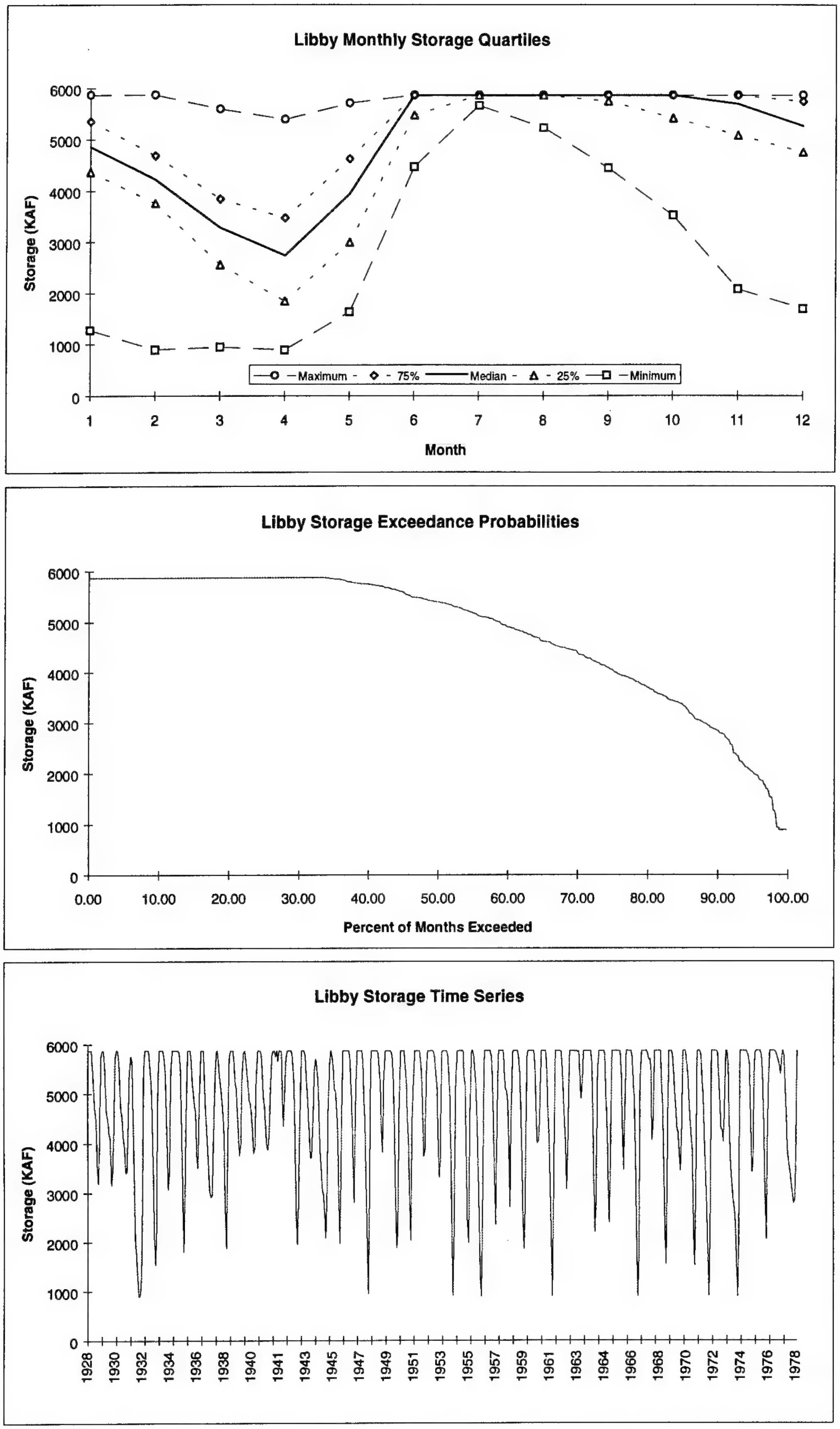
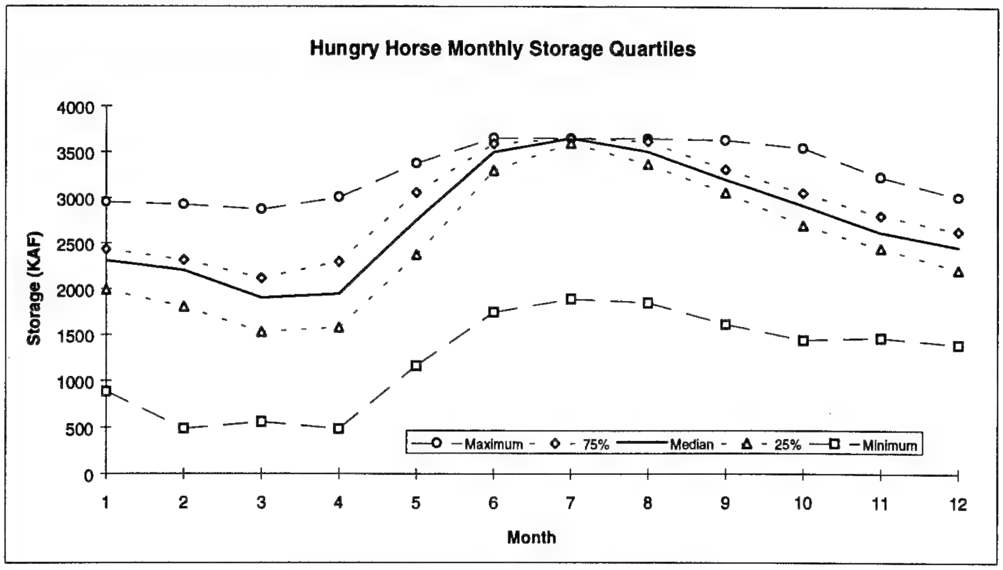
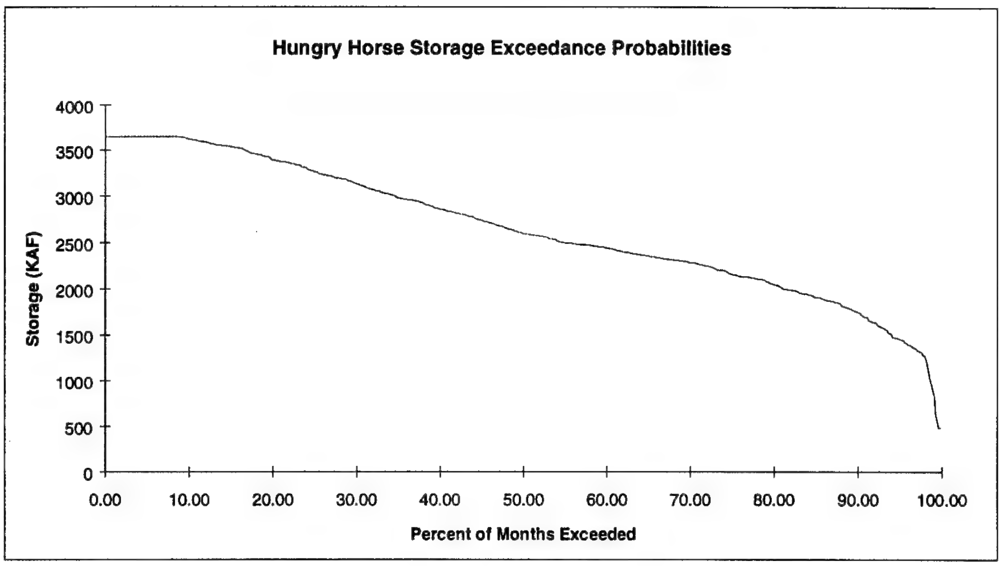


FIGURE 3.11 Libby Storage Results for Alternative 7





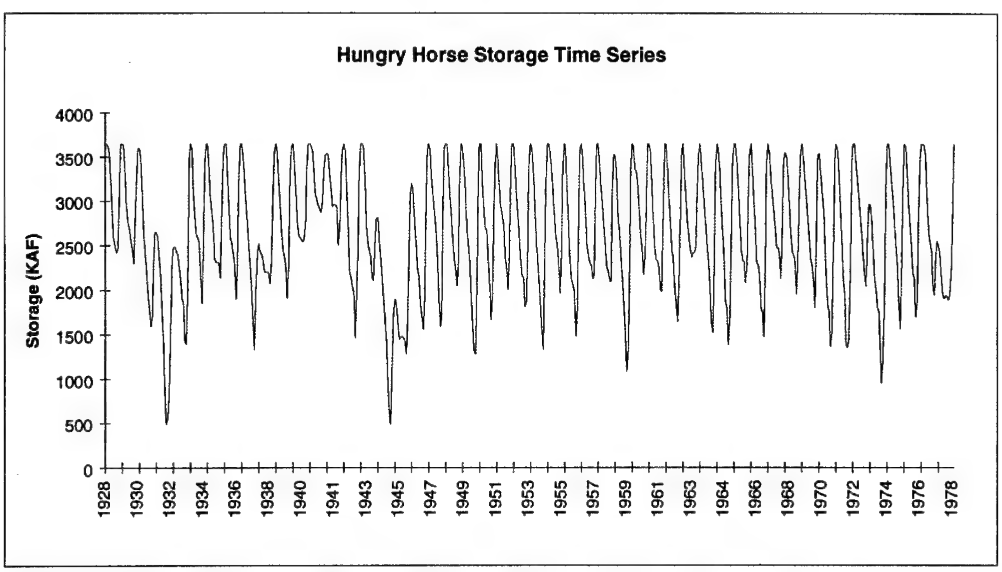


FIGURE 3.12 Hungry Horse Storage Results for Alternative 7

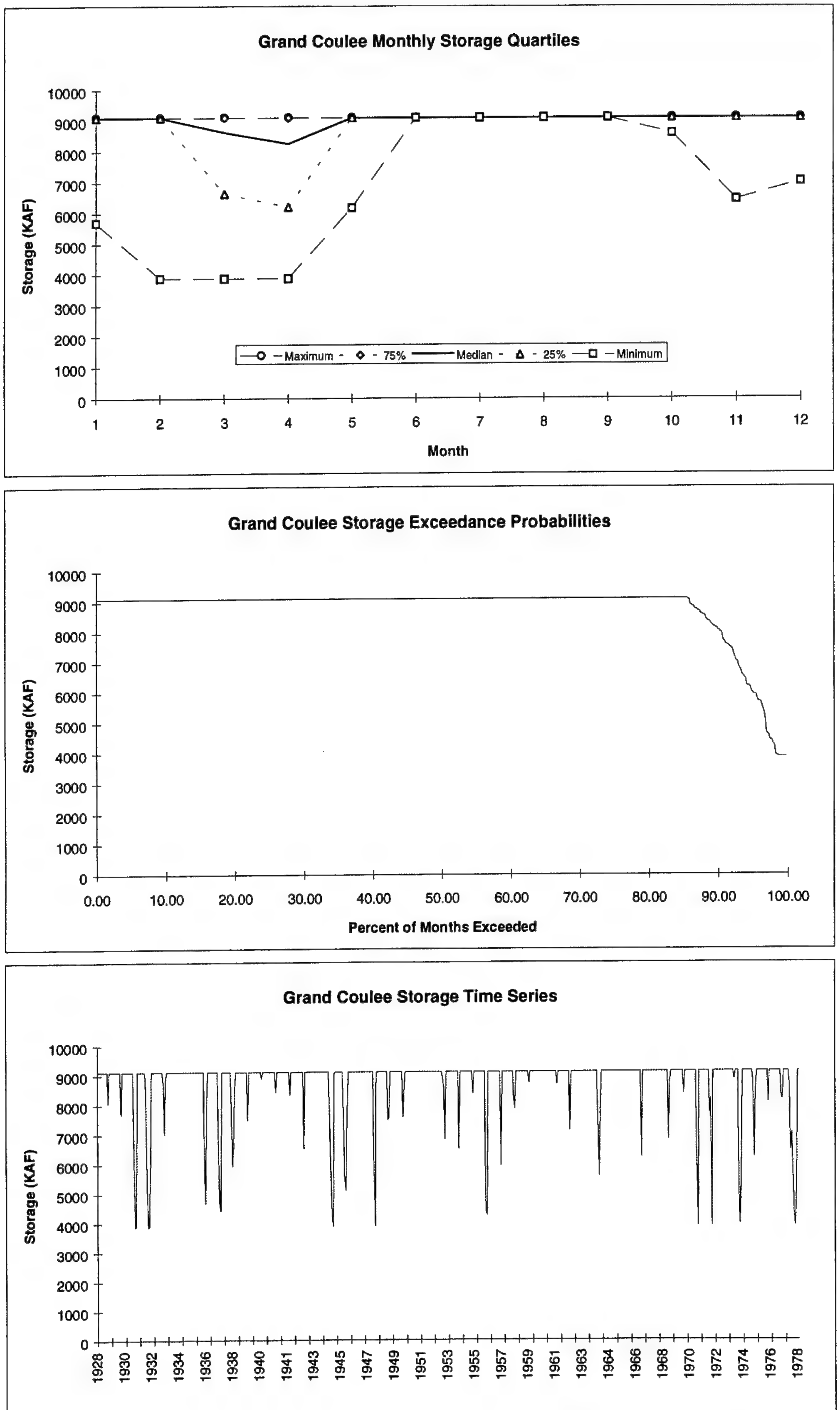


FIGURE 3.13 Grand Coulee Storage Results for Alternative 7

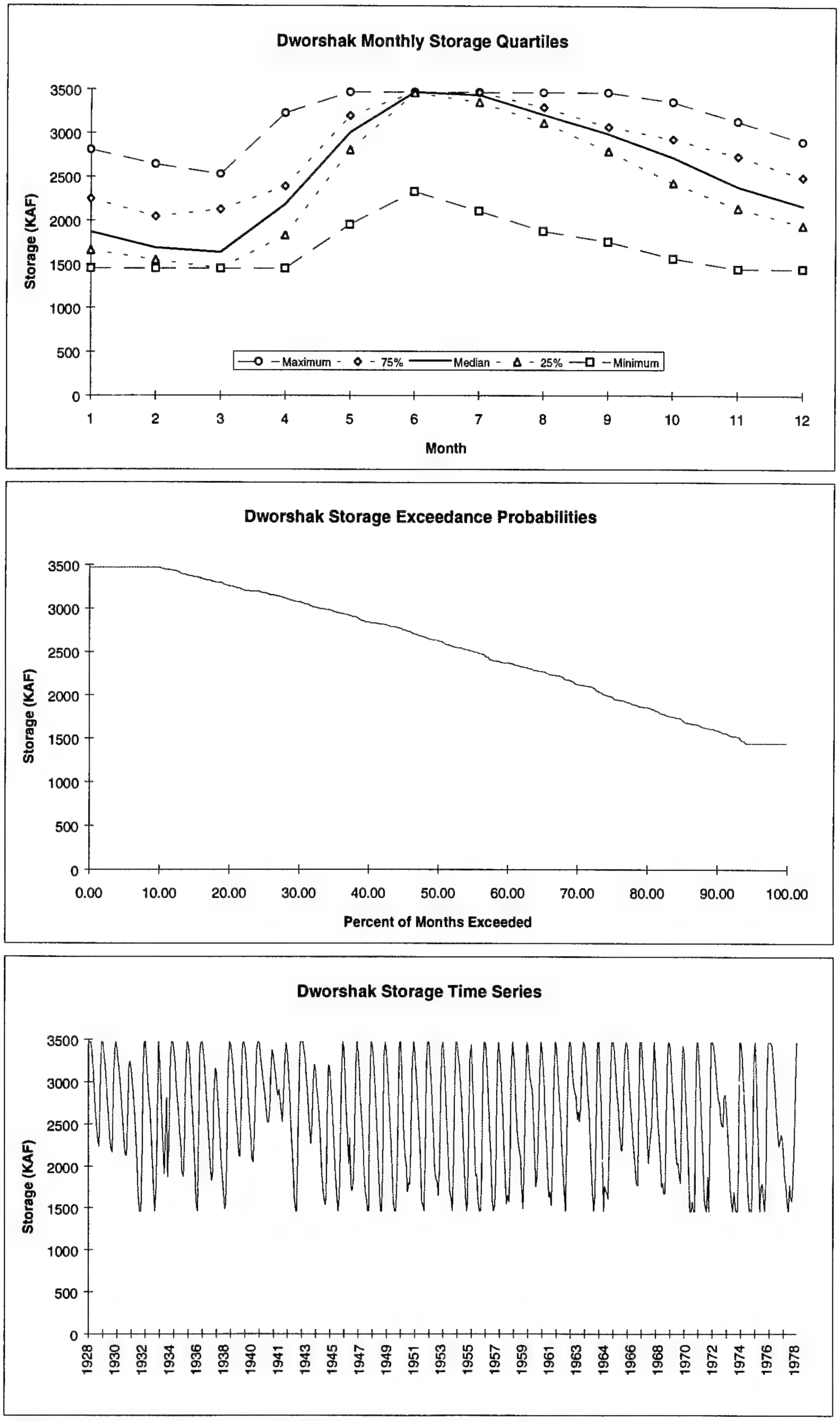


FIGURE 3.14 Dworshak Storage Results for Alternative 7

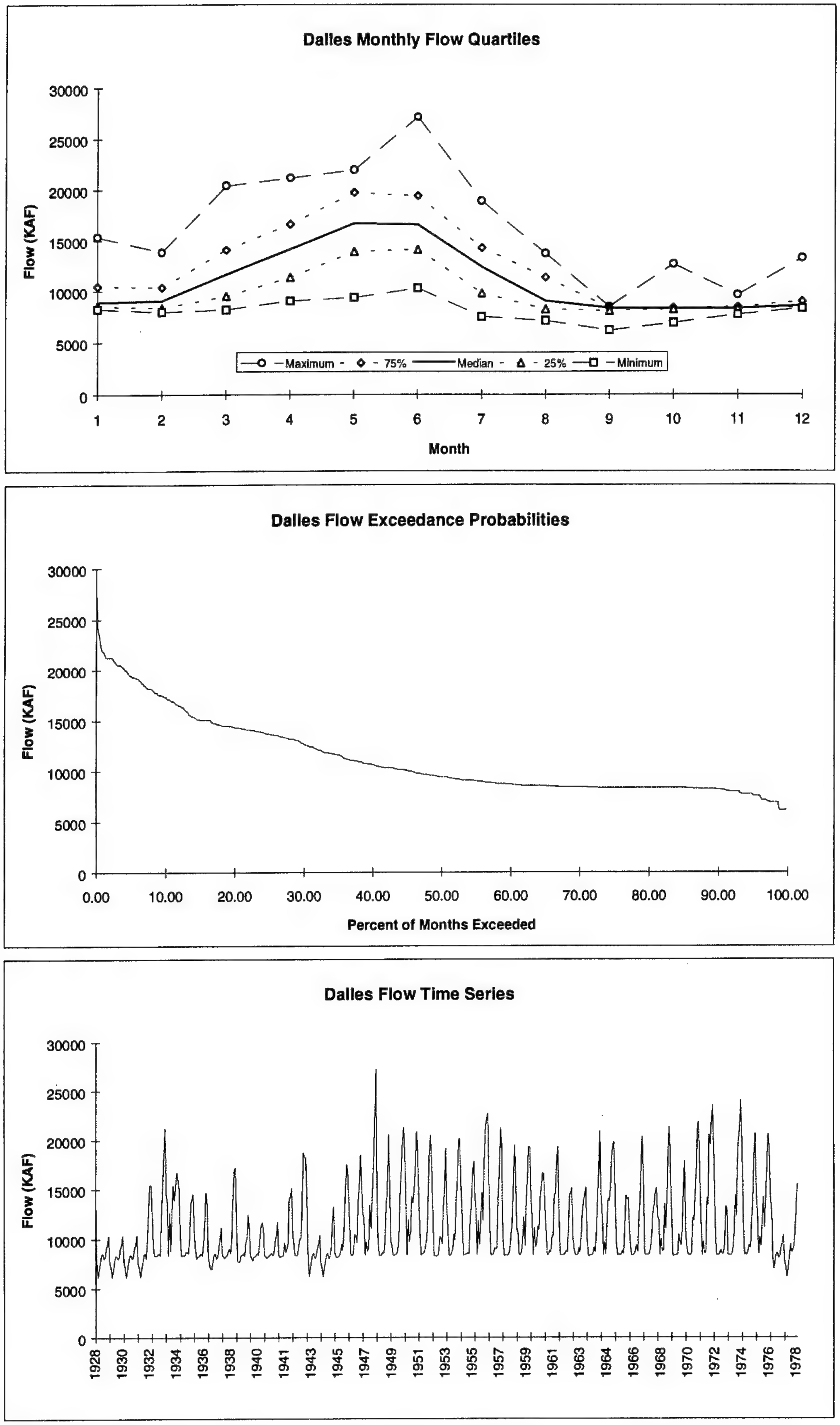


FIGURE 3.15 Flow Results at the Dalles for Alternative 7

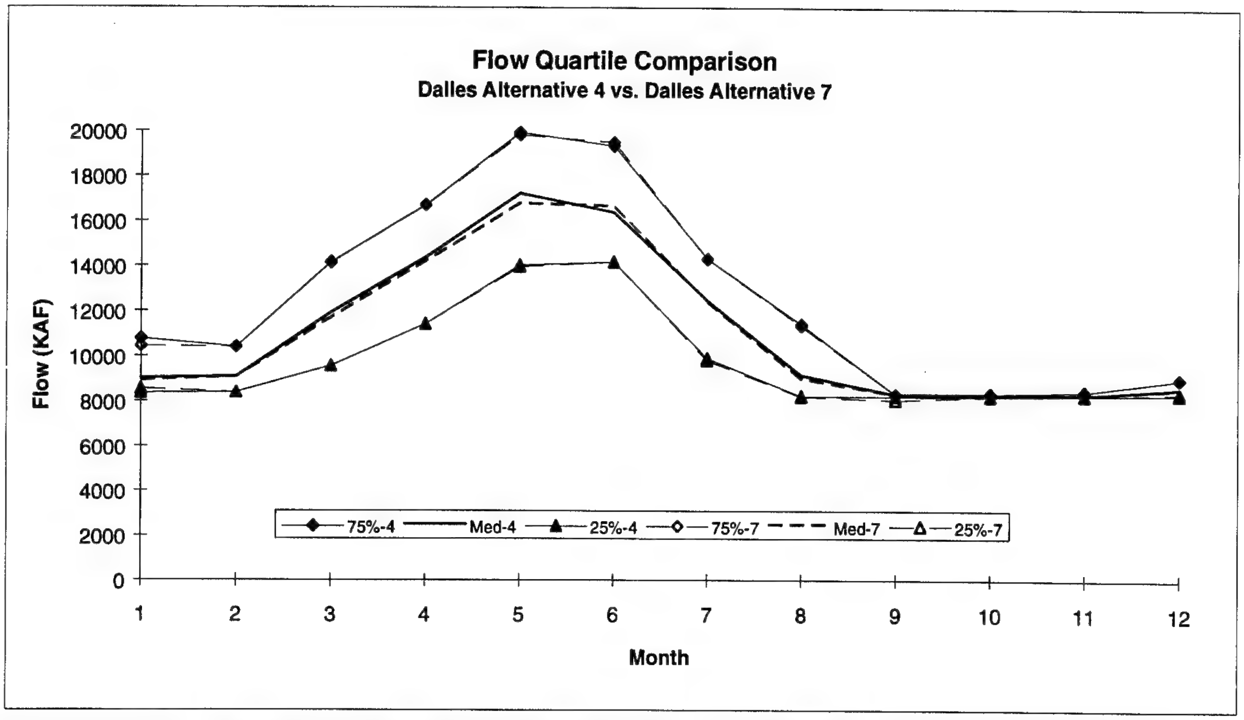


FIGURE 3.16 Effects on Flow at the Dalles from "Systemwide" Hydropower Penalty

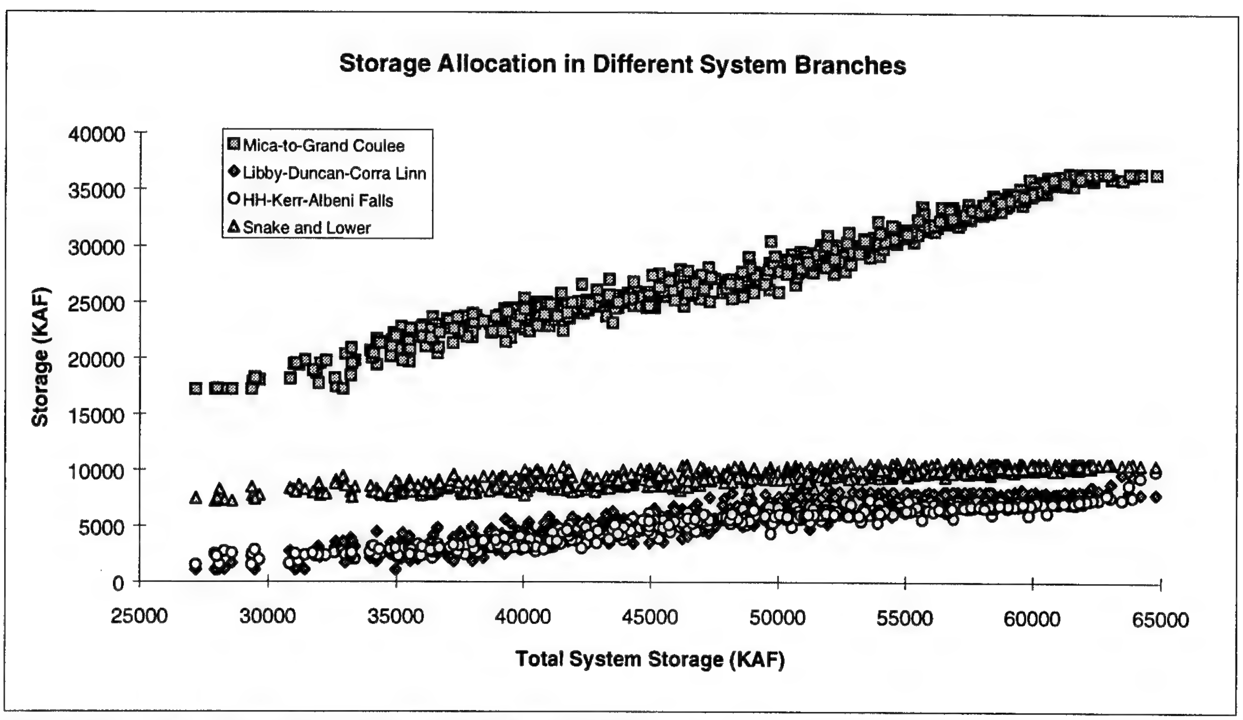


FIGURE 3.17 Storage Allocation by Branches

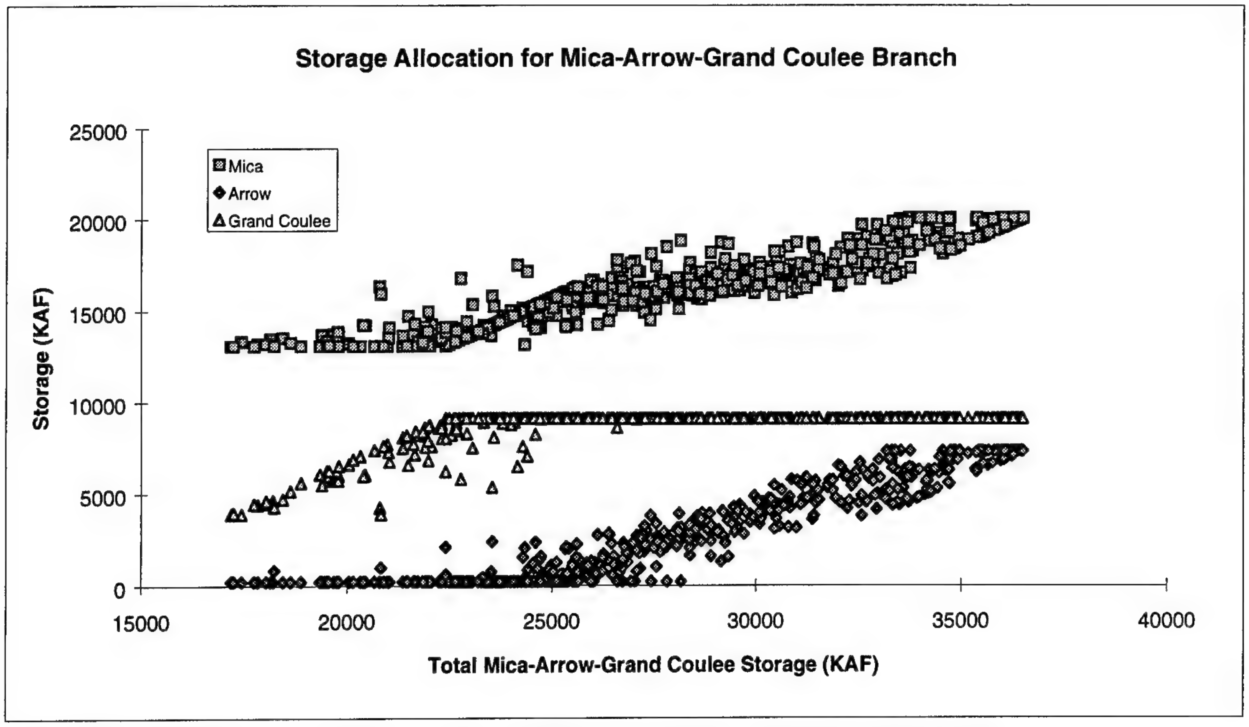


FIGURE 3.18 Storage Allocation for Mica-Arrow-Grand Coulee Branch

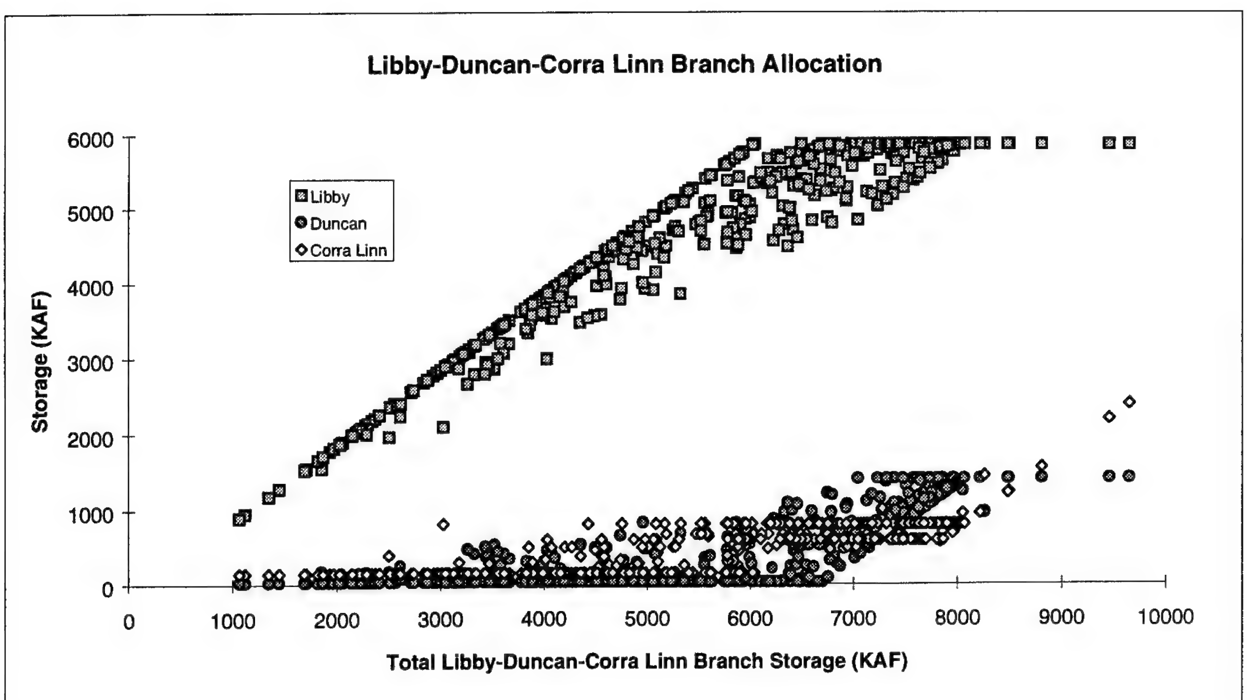


FIGURE 3.19 Storage Allocation for Libby-Duncan-Corra Linn Branch

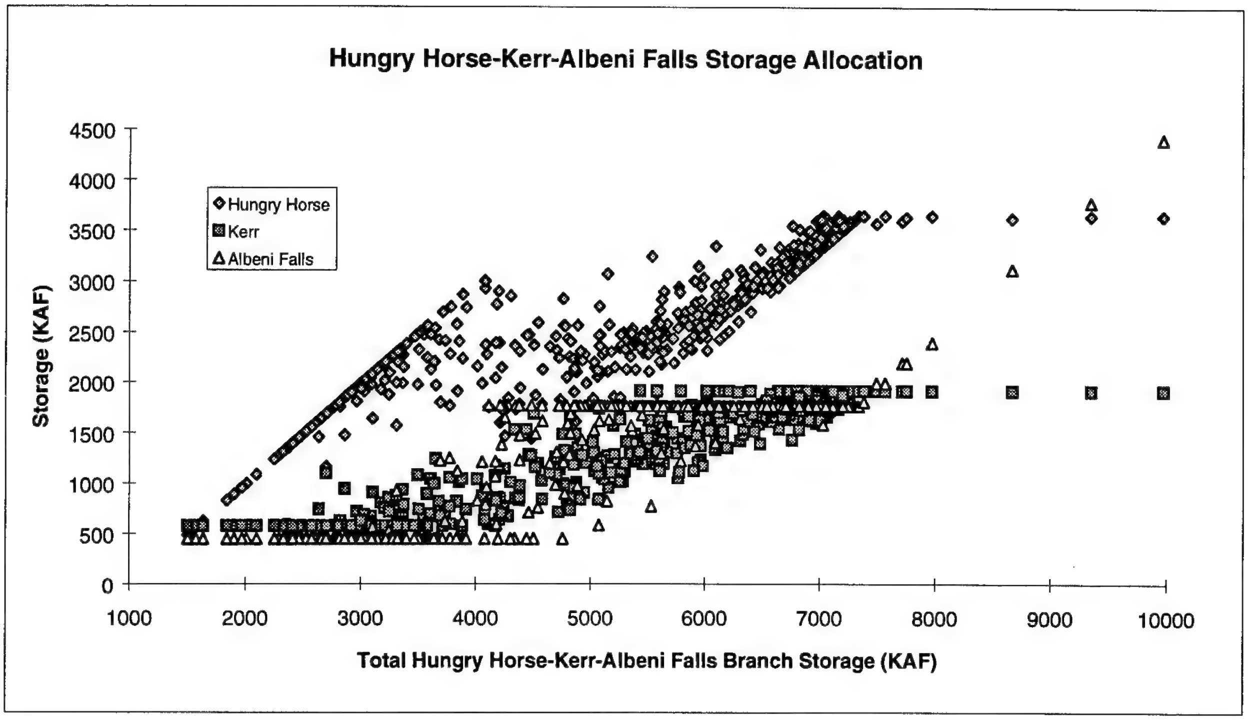


FIGURE 3.20 Storage Allocation for Hungry Horse-Kerr-Albeni Falls Branch

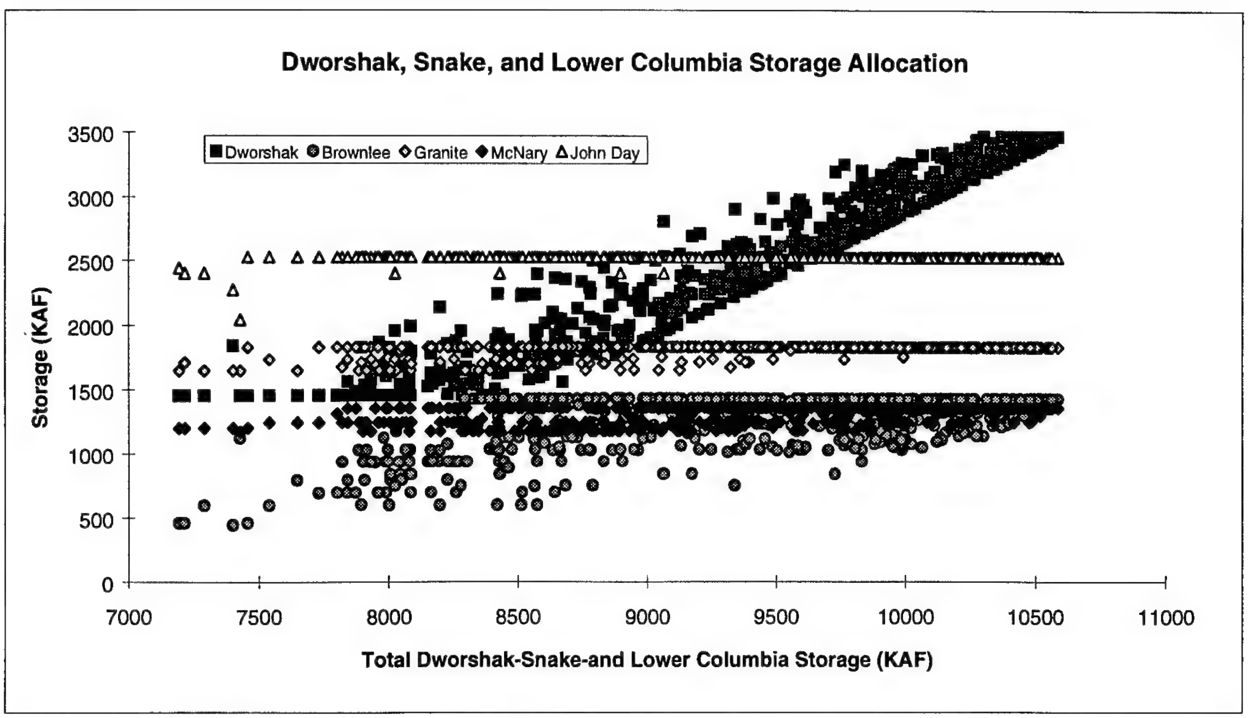


FIGURE 3.21 Storage Allocation for Dworshak, Snake, and Lower Columbia Reservoirs

Chapter 4

Comparison of Current Operations with HEC-PRM Results

4.1 Introduction

This chapter presents a comparison of current Columbia River system operations represented by HYSSR results and HEC-PRM operations for Alternative 7. Three types of plots are used to compare operations of the major reservoirs in the two models, (a) comparison of the middle three storage quartiles (25%, median, and 75%), (b) percent exceedance plots of storage, and (c) storage time-series plots over the 50-year analysis period. The quartile plots describe operation in the middle 50% of operating years, probably a good basis for normal operations. In all these plots, HYSSR results are represented by solid lines and HEC-PRM results are represented by dashed lines. The comparison of system operations is organized by the same classification of reservoirs used in previous Chapters.

Note: A discrepancy was noticed in the total flow represented by the two models. It appears that the inflow hydrologies used for the HYSSR run is slightly different than the one used for the HEC-PRM study. This discrepancy is described in Appendix F.

John Day, McNary, and Granite Storage

Current operations for John Day, McNary, and Granite are as run-of-river plants. Current John Day operation (Figure 4.1) provides some regular seasonal operations, with about 300 KAF of operating storage. However, HEC-PRM operations (Figure 3.1) more closely approximate pure run-of-river operations. The time series comparison shows minor drawdowns occurring only during droughts and in anticipation of floods.

McNary operations (Figure 4.2) are strictly run-of-river under HYSSR operations. HEC-PRM operations tend to keep the reservoir slightly fuller (about 45 KAF) most of the year, with drawdowns during January (about 150 KAF below HYSSR levels) and March and April (about 60 KAF below HYSSR levels). However, under HEC-PRM operations, McNary operations frequently fills and empties the available storage several times a year. Drawdown to the lowest allowable levels occurs briefly in about 86% of the years. This operating range is less than 200 KAF, less than one average day's streamflow for this part of the river.

Granite operations (Figure 4.3) also are strictly run-of-river under HYSSR. Operation under HEC-PRM is much less regular, somewhat more run-of-river than McNary and less so than for John Day. Several drawdowns may occur during a year, most frequently during January, March, and April. Complete allowable drawdown occurs in only 56% of the years. The operating range under HEC-PRM is only about 175 KAF, less than one day's average streamflow on the lower Columbia River.

Albeni Falls, Kerr, and Corra Linn Storage

Operation of Albeni Falls, Kerr, and Corra Linn reservoir storages is regular, but seasonally varying, under both HYSSR and HEC-PRM. For Albeni Falls (Figure 4.4), HEC-PRM tends to maintain a higher pool (about 250 KAF) between June and January, with drawdown between March and April. [(Some of this difference could be due to incorrect specification of the storage penalty function.)] Storage during February and May varies. HYSSR draws down storage earlier in the year, from September to November, with refill beginning in February and typically complete by June. HEC-PRM occasionally allows over-filling of the reservoir during flood events, a rarer occurrence under HYSSR.

Operation of Kerr reservoir (Figure 4.5) is more similar between HEC-PRM and HYSSR. Typical full levels for HEC-PRM are about 100 KAF more than under HYSSR, with similar drawdown seasons. HEC-PRM tends to retain a little lower drawdown level for about a month longer, with more rapid refill than under HYSSR.

Corra Linn operation (Figure 4.6) is even more similar between HEC-PRM and HYSSR than for Kerr. This largely results from use of penalties in HEC-PRM which reflect the current operating rules from the International Joint Commission. HEC-PRM over-fills Corra Linn less frequently, with anticipation of flood flows frequently leading to earlier drawdown. During droughts, Corra Linn is also kept empty longer and drawn down sooner under HEC-PRM.

Major Storage Reservoirs

Mica operations (Figure 4.7) are similar between HYSSR and HEC-PRM. The exception is the somewhat earlier drawdown by HEC-PRM between September and November. Refill typically occurs at similar rates and times. During droughts, HEC-PRM is less likely to refill Mica. HEC-PRM is also capable of drawing Mica down in anticipation of flooding several months in the future.

Both HYSSR and HEC-PRM typically use the entire operating range of Arrow each year (Figure 4.8). However, HEC-PRM generally refills Arrow more quickly and draws Arrow down earlier. This occurs at a steady rate from refill in July until empty in January. During droughts, HEC-PRM tends to refill Arrow less than HYSSR operations. In 1972-73, HEC-PRM also kept Arrow nearly empty in anticipation of flood control operations.

For Duncan (Figure 4.9), the comparison of HEC-PRM and HYSSR operations is similar to Arrow. Both operations use available Duncan storage over the year. HEC-PRM typically draws Duncan down more gradually, beginning earlier in the year and refills Duncan a little faster. HYSSR operation of Duncan is less variable between years than HEC-PRM. HEC-PRM's rate of draw-down during the fall and winter varies widely annually.

Libby's operation (Figure 4.10) is different between HEC-PRM and HYSSR results with both having a strong annual drawdown-refill cycle. HEC-PRM tends to fill Libby about one month earlier, keeps Libby full for almost three months longer, completes drawdown about 2 months later, and typically draws down about 1 MAF less than HYSSR operations. For drought and flood years, extreme Libby drawdowns are similar between HEC-PRM and HYSSR, drawing down to about 1 MAF of storage. HEC-PRM operations refill Libby more frequently in dry years. HEC-PRM refills or comes close to refilling Libby in every year of the 50-year analysis.

Hungry Horse (Figure 4.11) appears to have a different storage-elevation curve between the HYSSR and HEC-PRM studies giving the HEC-PRM representation of Hungry Horse about 500 KAF of additional storage capacity. HEC-PRM begins drawdown a month or two earlier than HYSSR operations. Neither HYSSR nor HEC-PRM are able to refill Hungry Horse during drought years. HYSSR typically draws down further during these than does HEC-PRM. Flood operations appear similar between the two models.

HEC-PRM's Grand Coulee operations (Figure 4.12) are generally near-run-of-river with frequent brief drawdowns and refill during March and April, typically to levels less severe than under HYSSR operations. Most of the infrequent deep drawdowns by HEC-PRM are similar to HYSSR levels during drought or flood years.

Dworshak operations (Figure 4.13) are similar to HYSSR, with comparable amplitudes of drawdown and refill. HEC-PRM tends to draw Dworshak down several months earlier than HYSSR. HEC-PRM operations also tend to more closely approach a full level during drought years.

Flows at The Dalles

Flows at The Dalles (Figure 4.14) show a little different seasonal operation between HEC-PRM and HYSSR. HEC-PRM flows at the Dalles tend to be a 1-2 MAF/month higher than HYSSR flows during the fall, about 7 MAF/month lower during January, about 1 MAF/month lower in February, about the same in March, and a little higher in April. Dalles flows in June and July are 2-3 MAF/month greater for HEC-PRM operations.

Overall, as the flow exceedance comparison plot (Figure 4.14) illustrates, HEC-PRM tends to dampen peak and low flows relative to HYSSR operations. The Dalles flood peaks are typically reduced significantly by foresighted HEC-PRM operations, and minimum flows are higher during most years.

During drought years, low flows from HEC-PRM operations roughly match HYSSR operations. This drought behavior is largely due to the system-wide hydropower penalties imposed on Dalles flows, where HYSSR drought flows were used to establish target flows with steep penalties. Without this system-wide hydropower constraint, Dalles flows under HEC-PRM were somewhat less than HYSSR flow results.

Figure 4.15 compares median, minimum, and maximum Dalles flows between unregulated (no reservoirs), HYSSR, and HEC-PRM operations. In both the median and minimum flow cases, HEC-PRM operations during the summer months (June through August) tend to be significantly greater than HYSSR flows, lying between unregulated and HYSSR operations. In these median and minimum flow cases, both HYSSR and HEC-PRM operations have higher September to March flows than unregulated operations. Maximum flows at The Dalles are typically less for both HEC-PRM and HYSSR operations than unregulated conditions between April and August. HYSSR maximum flows are much greater than unregulated of HEC-PRM flows during January, and slightly greater than HEC-PRM and unregulated flows during February and March. Both HEC-PRM and HYSSR maximum Dalles flows during September through December are greater than the unregulated flows.

Total System Storage

The behavior of system-wide storage for the Columbia River System reservoirs is compared for HYSSR and HEC-PRM operations in Figure 4.16. For most years, the plot comparing the middle quartiles of operation demonstrates fairly similar within-year operations. HEC-PRM operations tend to draw the system down a little more rapidly, and cease drawdown at a higher total storage level than HYSSR. Since system drawdown is less complete under HEC-PRM, refill can also proceed more quickly than under HYSSR. With these exceptions, filling and drawdown of system-wide storage are similar driven by seasonal hydrologic variability and the relatively small storage on the system with respect to mean annual flow. The time-series comparison of total system storage accentuates the similarity of HEC-PRM and HYSSR operations of total storage, particularly during droughts (Figure 4.17).

Still, the distribution of storage in the system can be significantly different between HEC-PRM and HYSSR operations.

Distribution of Storage

This section compares the allocation of system storage between HYSSR results and HEC-PRM Alternative 7. Two levels of comparison are presented. Branch storage versus total system storage and individual reservoirs versus their branch. Figure 4.18 shows the storage allocation for the branches of the system in relation to the total system storage for HYSSR results. This plot is comparable to Figure 3.17 for Alternative 7. The storage allocation data exhibits more scatter for HYSSR results. The largest difference between the two alternatives occurs on the Mica, Arrow, Grand Coulee branch. Figure 4.19 shows that Alternative 7 has a tighter band of storages that tend to be lower than the HYSSR results. The difference is most noticeable between total system storages of 40 and 55 MAF. Figure 4.20 compares the storage allocation for individual reservoirs in relation to the Mica, Arrow, Grand Coulee branch storage for the two alternatives. The storage for Arrow under Alternative 7 results are almost always lower than for HYSSR below branch storages of 25 MAF. However, Grand Coulee tends to be more full in Alternative 7 than in HYSSR. Mica appears about the same for branch storages above 25 MAF and lower for Alternative 7 below storages of 25 MAF. This indicates that HEC-PRM tends to lower Mica and Arrow as necessary to keep Grand Coulee as full as possible.

The storage allocation for the Libby, Duncan, Corra Linn branch is compared on Figure 4.21. The general trend shows that Alternative 7 allocates a larger percentage of total system storage to this branch than HYSSR, especially above 42 MAF. This difference seems mostly in Libby storage. Figure 4.22 shows that Libby storage in Alternative 7 is almost always higher than HYSSR. Allocations for Duncan seem to be slightly less for most branch storage values in Alternative 7, but the differences are not as significant as for Libby.

The comparison of storage allocation for the Hungry Horse, Kerr, Albeni Falls branch also shows some noticeable differences (Figure 4.23). For total system storages above 43 MAF Alternative 7 allocates more storage to this branch than does HYSSR. For total system storages below 43 MAF Alternative 7 values are lower than most of the storages from HYSSR, but never as low as the lowest values for HYSSR results. Figure 4.24 compares the storage allocations for Hungry Horse with respect to the Hungry Horse, Kerr, Albeni Falls branch storage. This comparison should be viewed with caution due to the likely difference between storage to elevation curves used in the two alternatives (discussed in Chapter 4). It appears that the two alternatives result in a similar storage allocation pattern of a strongly discernable slope from full to empty, but still with considerable scatter. The higher reservoir storages for the HEC-PRM results are likely due to the differing reservoir capacity data. One observation that could be useful however, is that the HEC-PRM results show the reservoir drawdown - refill cycle frequently occurs at higher branch storage values than the HYSSR results. Figure 4.25 shows a similar trend for the Kerr reservoir. The Alternative 7 results indicate that Kerr is often drawn down and refilled at higher branch storage levels than in HYSSR.

The comparison of storage allocation for the Snake and Lower Reservoirs branch is shown on Figure 4.26. This plot indicates variations in the allocation pattern, but differences appear so slight that it is difficult to reach any significant conclusions. This is not surprising since three of the reservoirs are essentially operated as run of river reservoirs and Brownlee was represented in the HEC-PRM study using the results from the HYSSR output. Thus the only reservoir that could differ significantly is Dworshak.

4.2 Some Limitations of Comparison

In examining the results several limitations of the above comparisons became evident. These are reviewed below.

Conservation of Mass

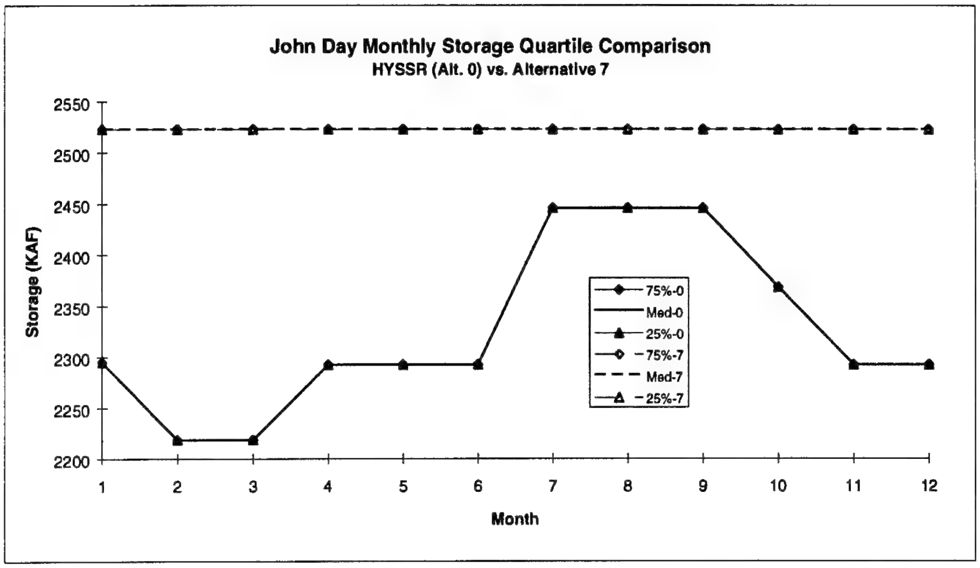
Summing all system outflows over the 50-year period, the HEC-PRM model releases about 182 MAF of water more than the HYSSR results used in this comparison. If distributed evenly over the 50-year analysis period, this results in about 3.6 MAF of additional water available in the HEC-PRM model each year. This is not a large amount of water in a system with a mean annual outflow of almost 130 MAF, but can be substantial during extreme drought years. See Appendix F for details.

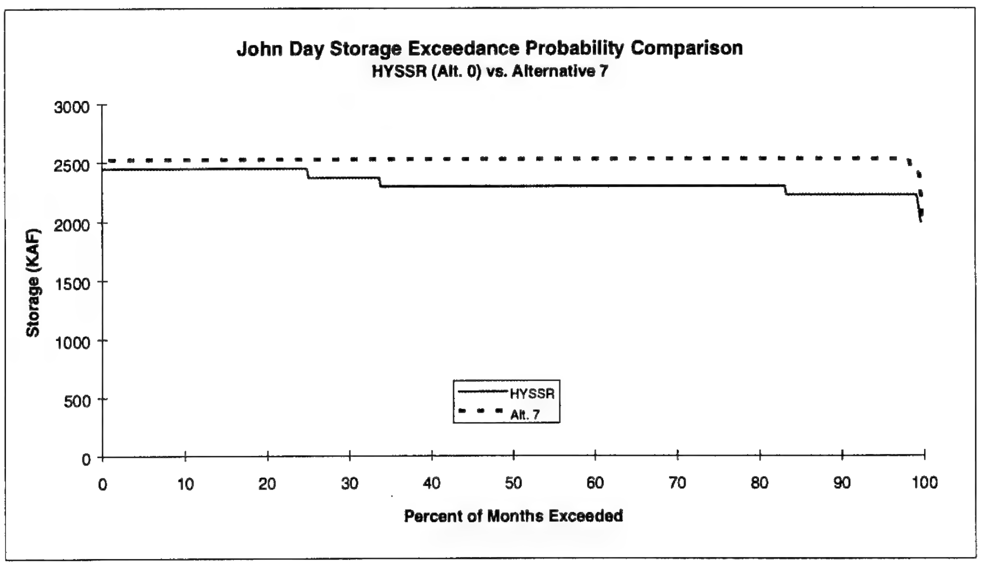
Foresight

HEC-PRM, being a deterministic optimization model, has perfect foresight over the 50-year analysis period. Such foresight is probably inappropriate for operation for over-year drought events and short-term flood events, where additional water might be retained or released in anticipation of practically unknown future events.

4.3 Conclusions

The comparison of HYSSR and HEC-PRM results show some strong similarities as well as noteworthy differences. The behavior of system-wide storage is similar for the two alternatives. The significant differences arise in the way in which the storage is allocated within the system, particularly for the major reservoirs. Alternative 7 allocates less storage in the Mica, Arrow, Grand Coulee branch while allocating more storage in the Libby, Duncan, Corra Linn branch and the Hungry Horse, Kerr, Albeni Falls branch than HYSSR. While the Mica, Arrow, Grand Coulee branch usually contains less of the total system storage under Alternative 7, Grand Coulee consistently holds more of the storage placed in that branch than under the HYSSR output. These results seem to place great importance on keeping Grand Coulee full. Water is released from Arrow (which has no hydropower facilities) to maintain full levels at Grand Coulee. The higher allocations for the Libby, Duncan, Corra Linn and the Hungry Horse, Kerr, Albeni Falls branches likely occur to maximize the benefit gained from the water released from the reservoirs at the highest elevations. In other words, water stored and released from the Hungry Horse reservoir is used for power generation at Hungry Horse, Kerr, and Albeni Falls before it reaches Grand Coulee. On the other hand, water released from Mica only contributes to power generation at Mica before it reaches Grand Coulee. The Alternative 7 results indicate that HEC-PRM gives more preference to lowering the pools in Mica and Arrow to keep Grand Coulee full than under the HYSSR operation.





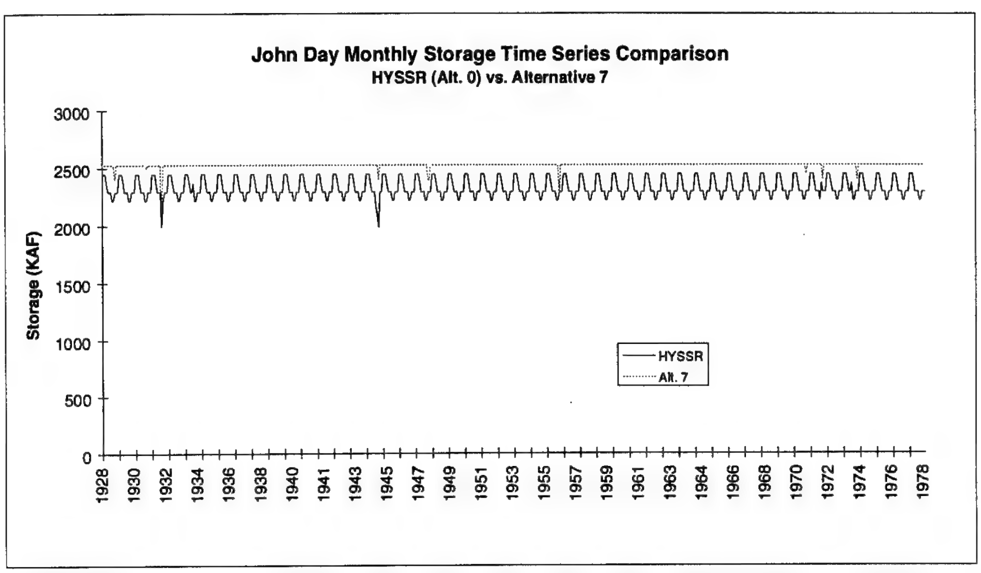
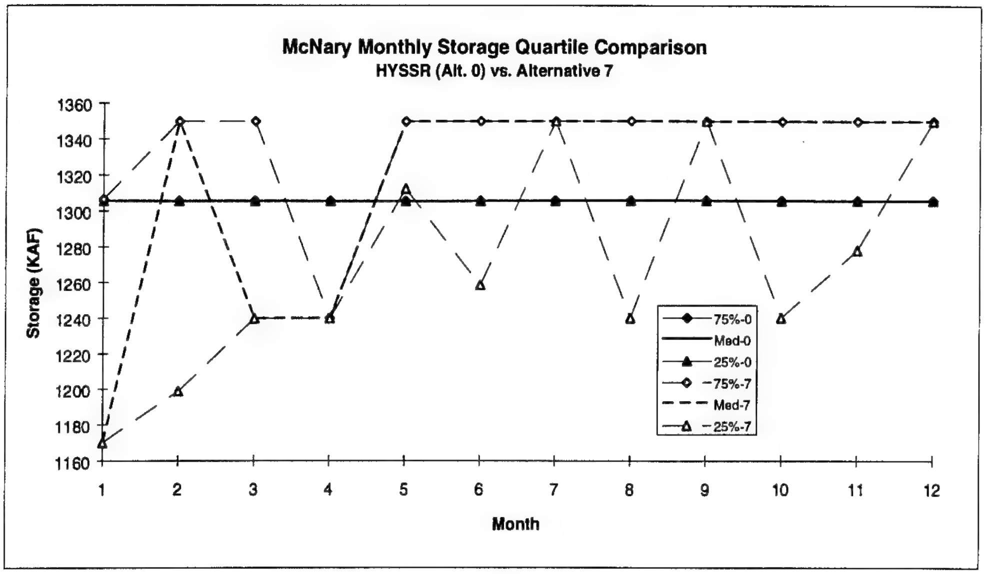
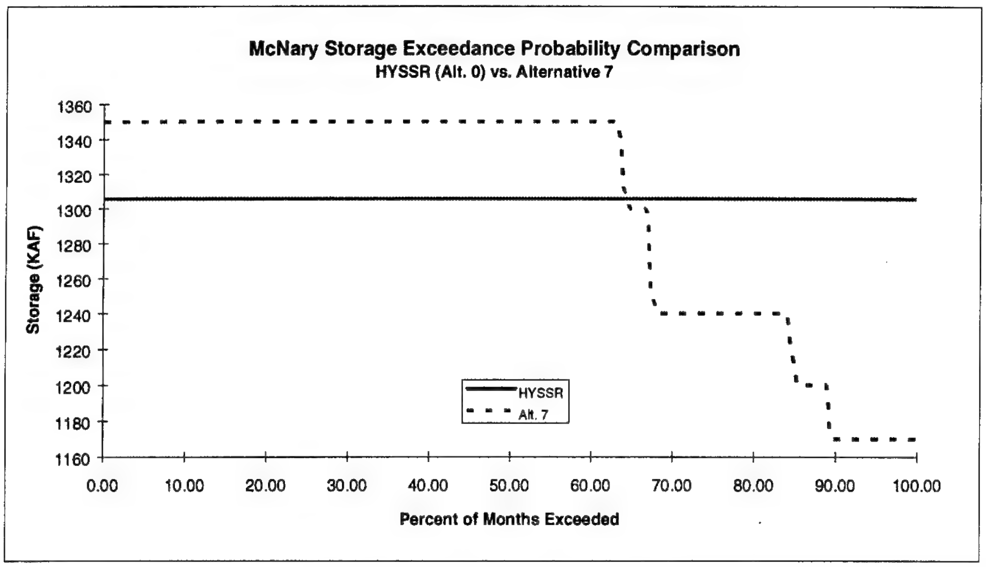


FIGURE 4.1 Comparison for John Day Storage: HYSSR vs. Alt. 7





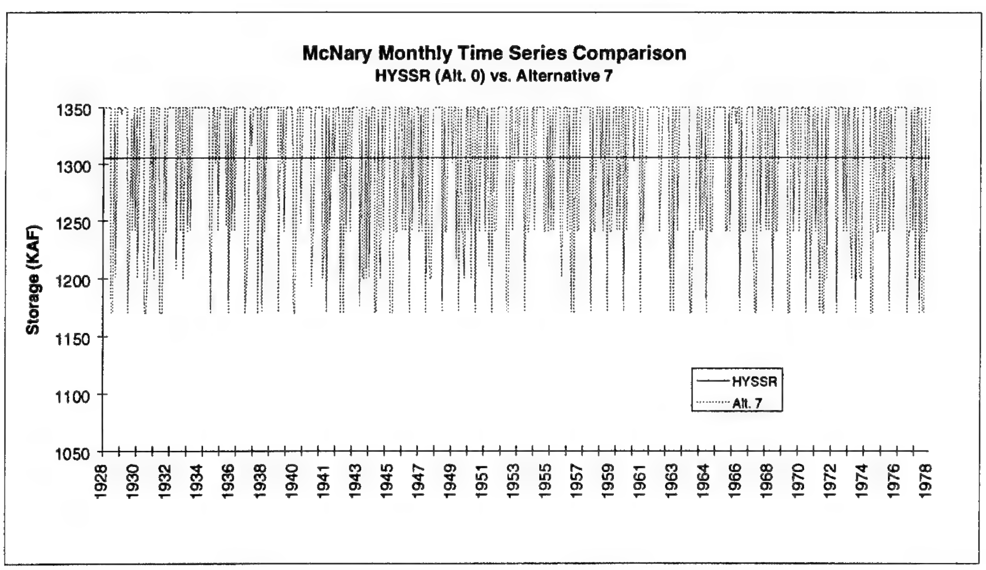
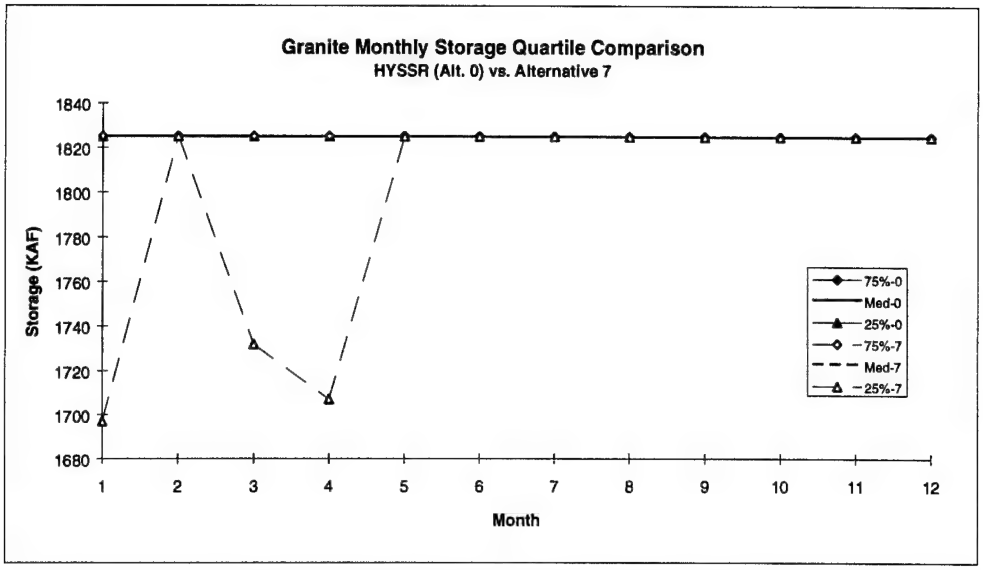
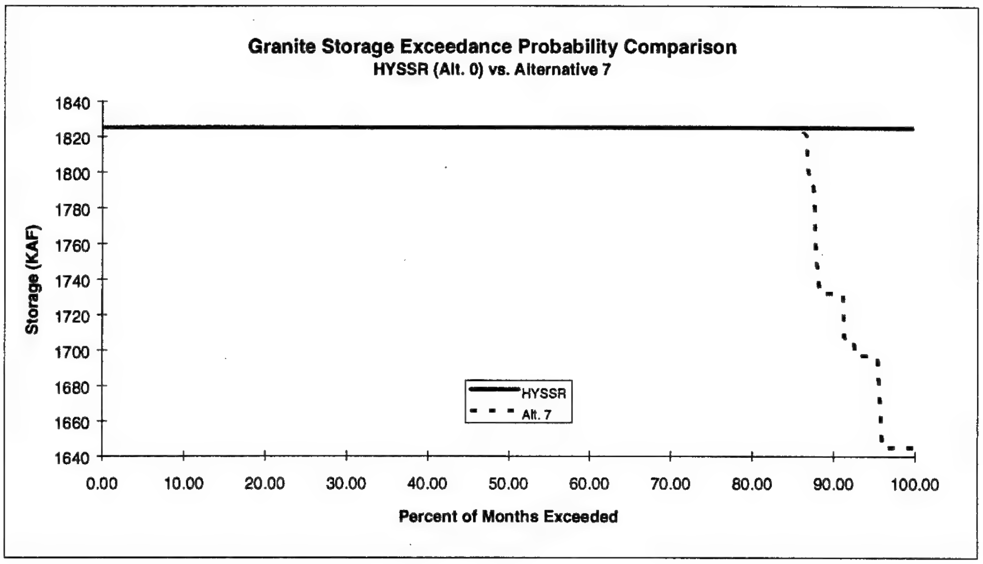


FIGURE 4.2 Comparison for McNary Storage: HYSSR vs. Alt. 7





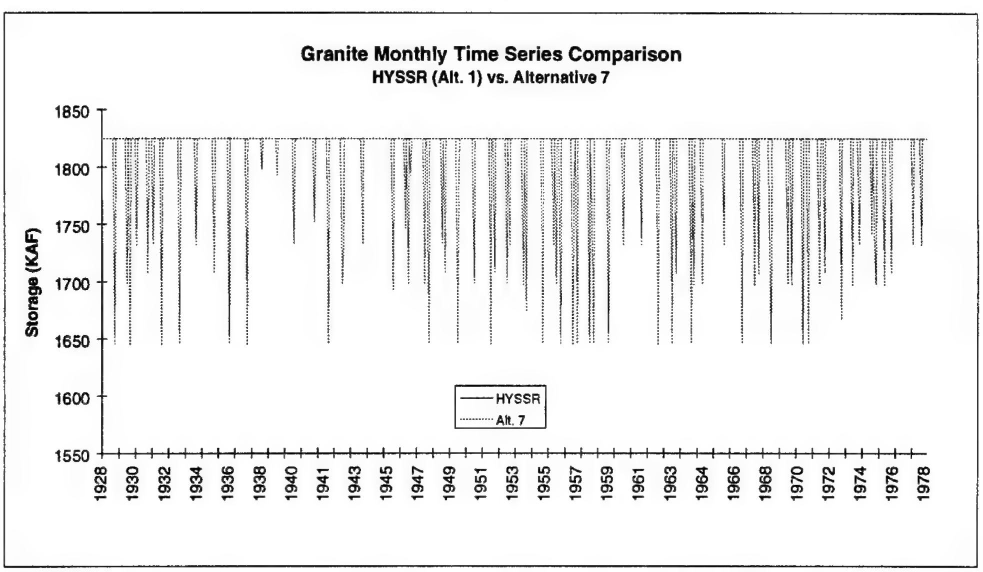
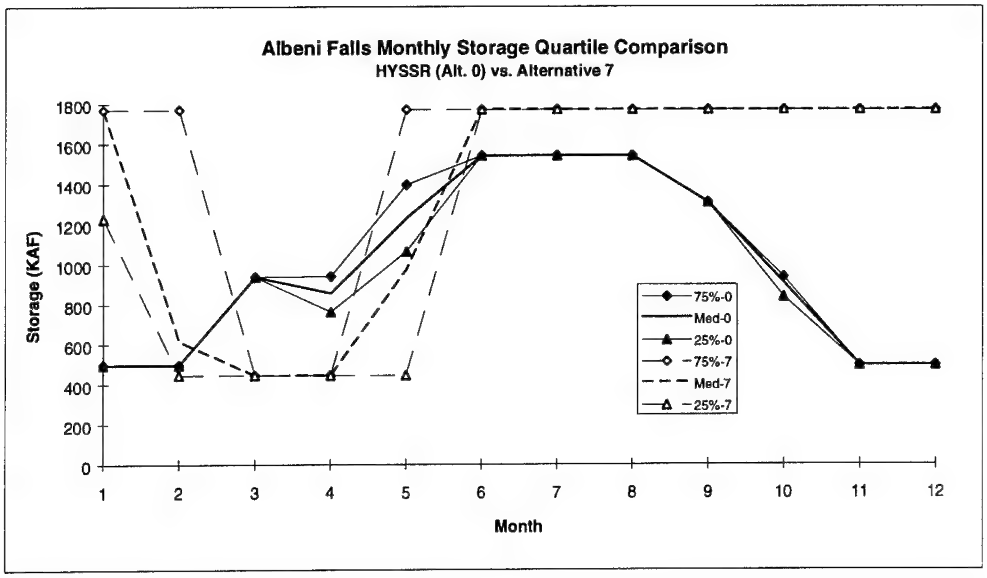
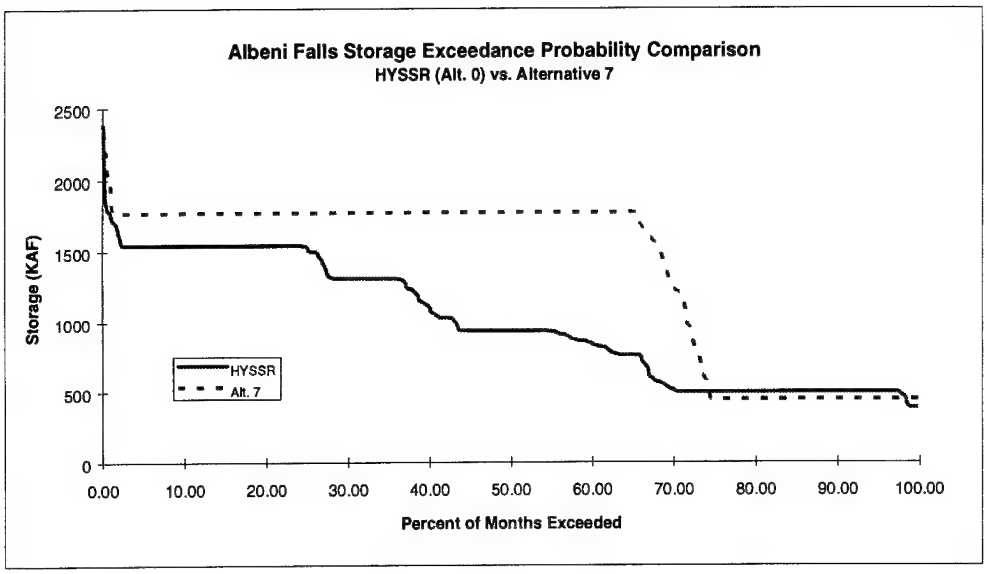


FIGURE 4.3 Comparison for Granite Storage: HYSSR vs. Alt. 7





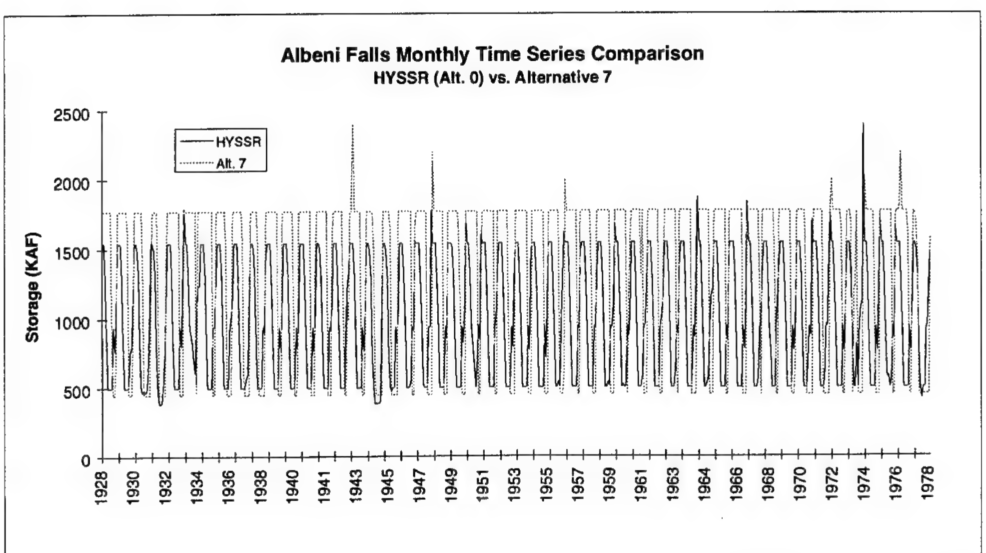


FIGURE 4.4 Comparison for Albeni Falls Storage: HYSSR vs. Alt. 7

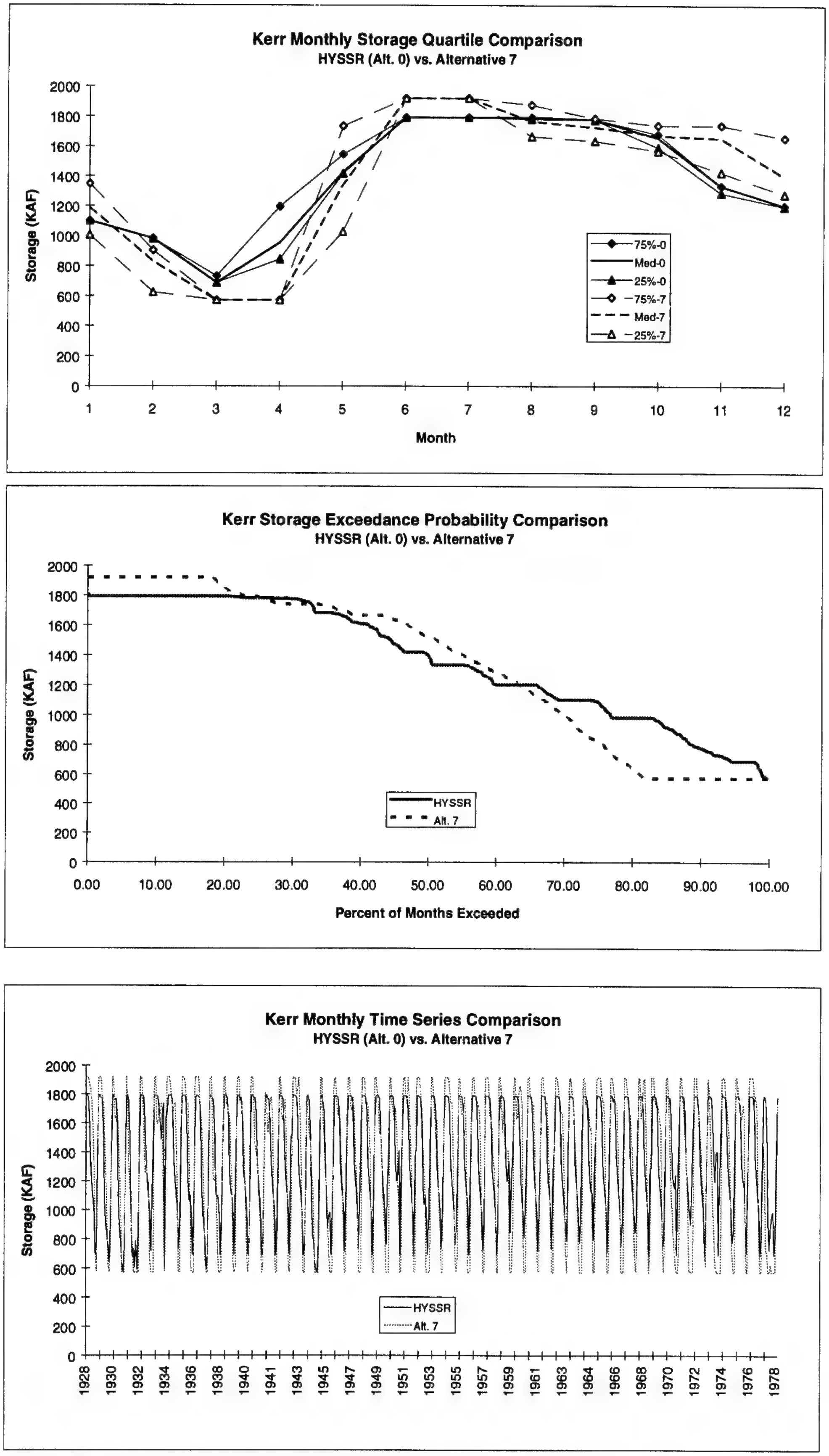
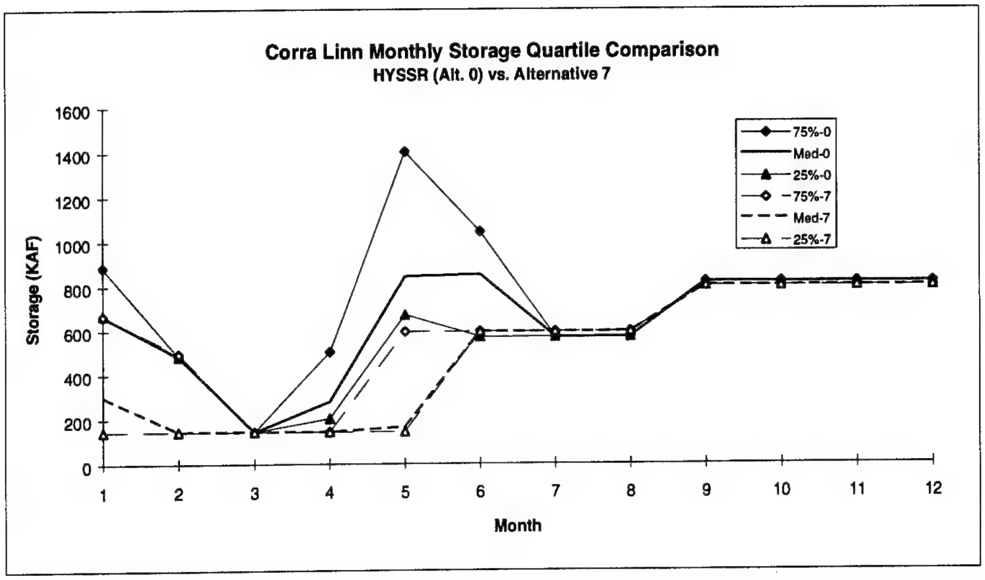
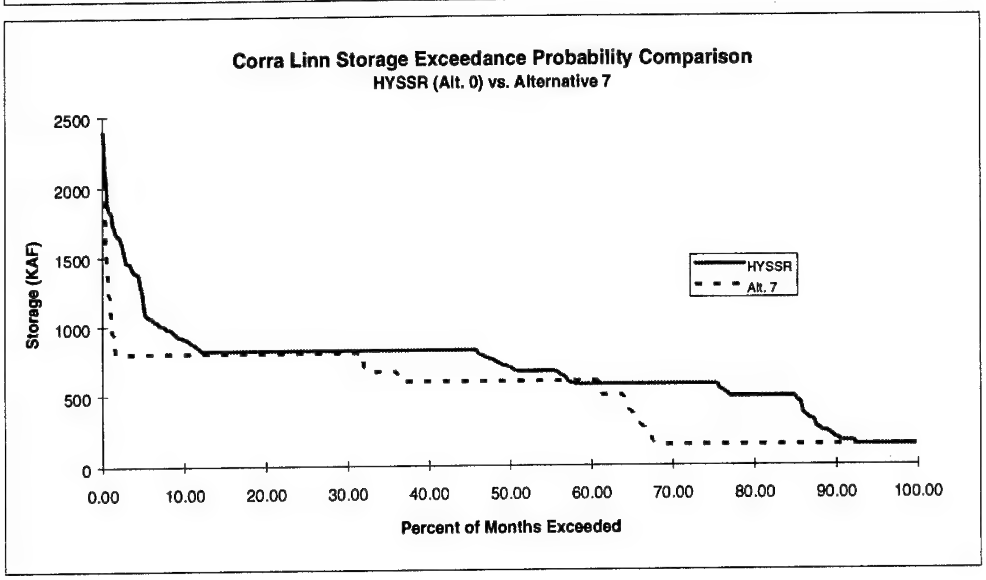


FIGURE 4.5 Comparison for Kerr Storage: HYSSR vs. Alt. 7





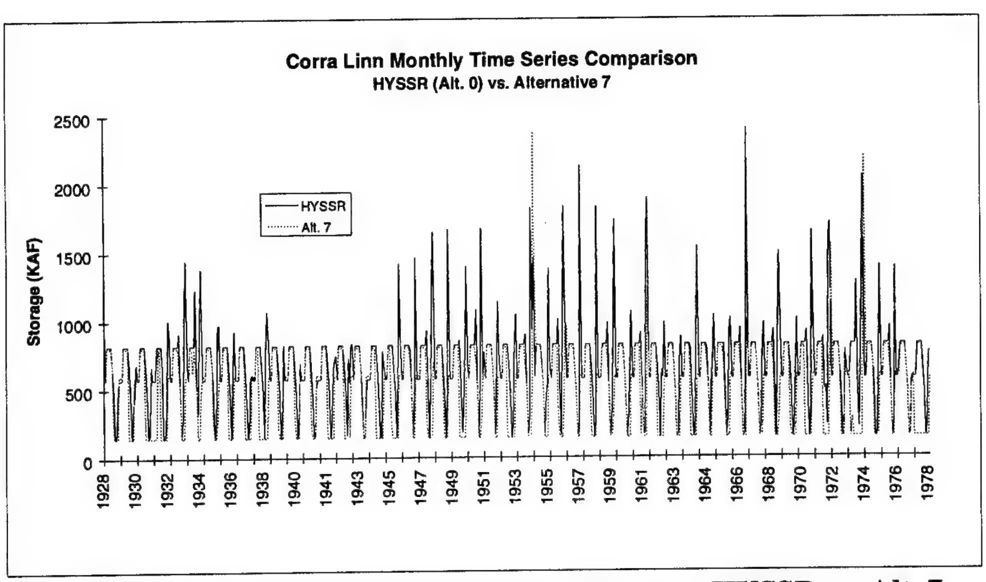
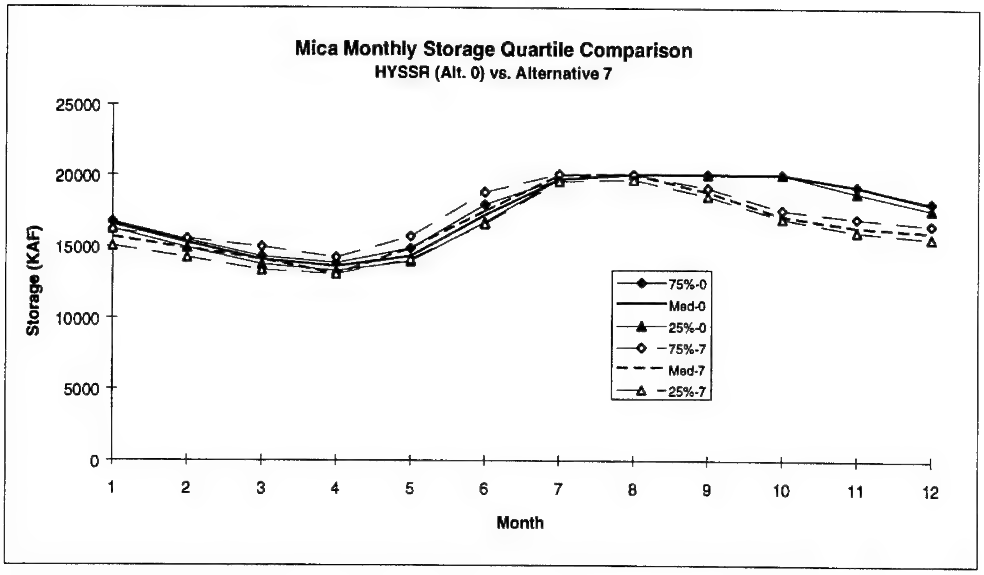
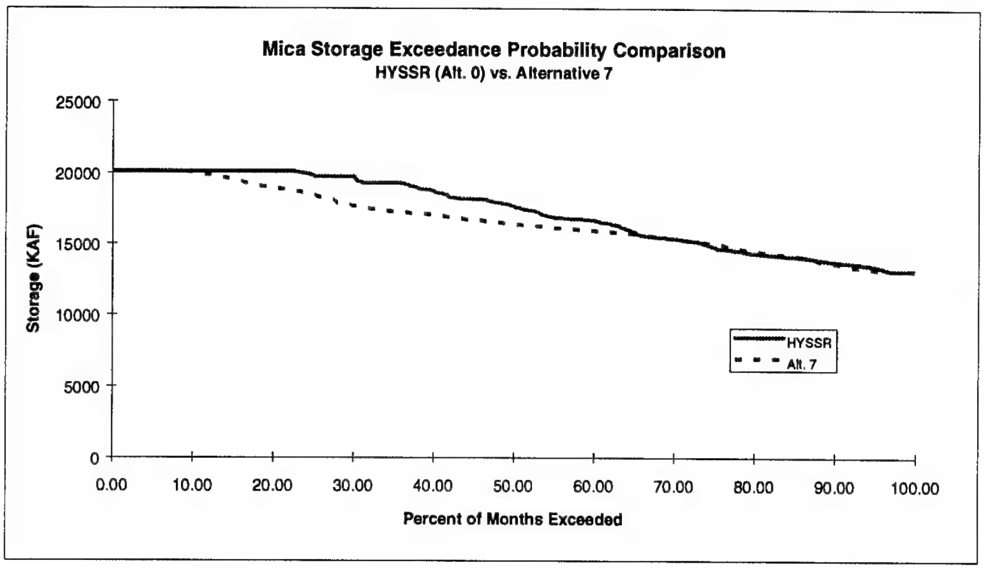


FIGURE 4.6 Comparison for Corra Linn Storage: HYSSR vs. Alt. 7





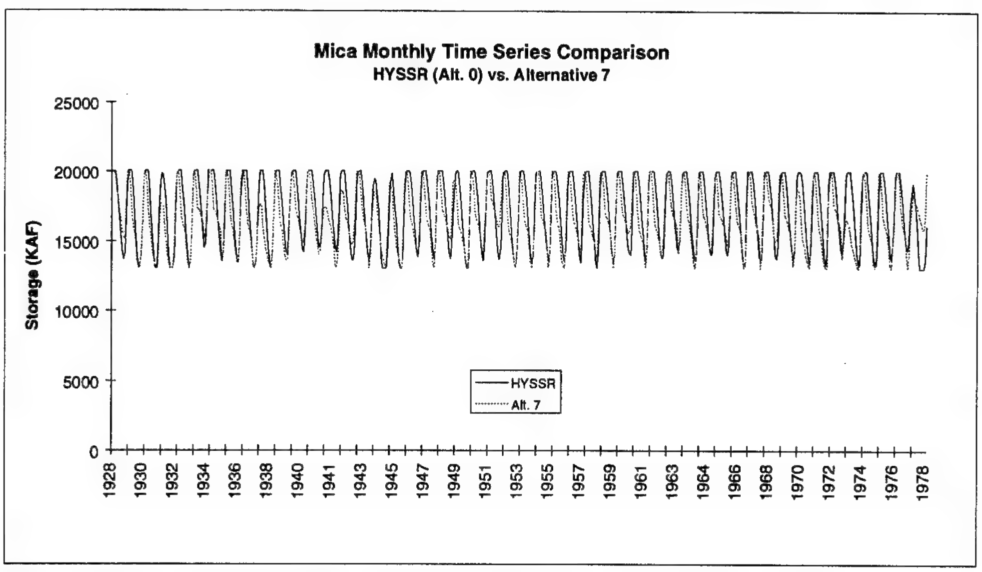
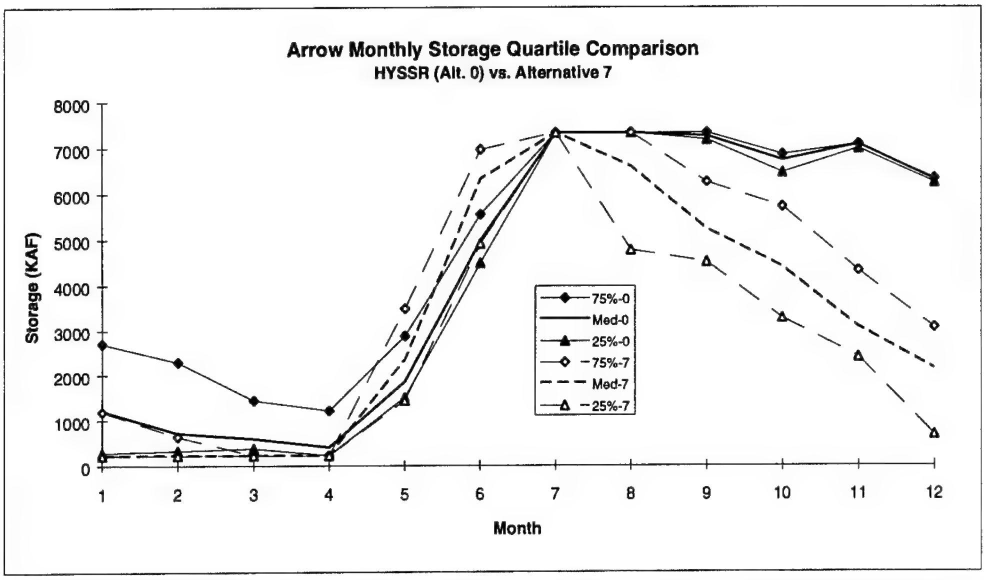
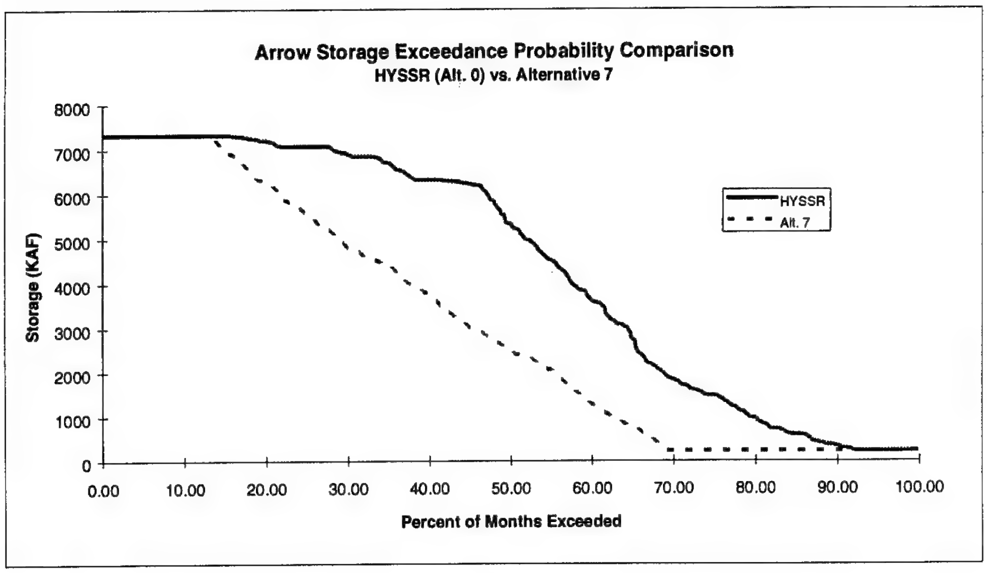


FIGURE 4.7 Comparison for Mica Storage: HYSSR vs. Alt. 7





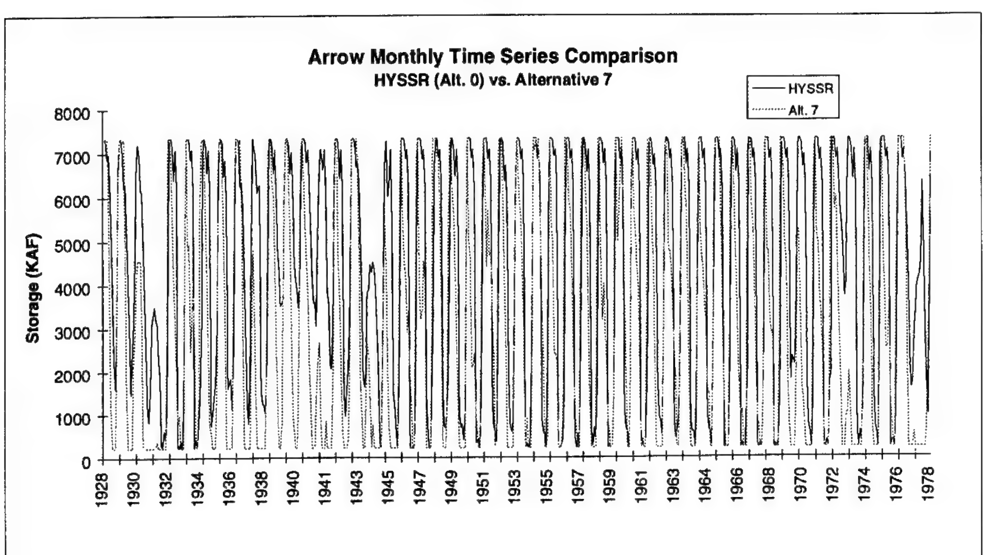
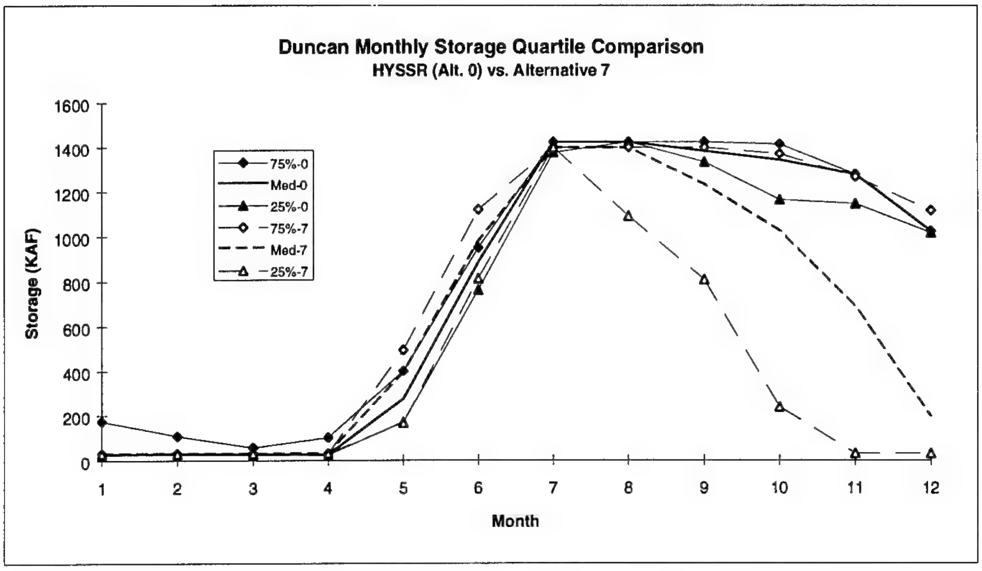
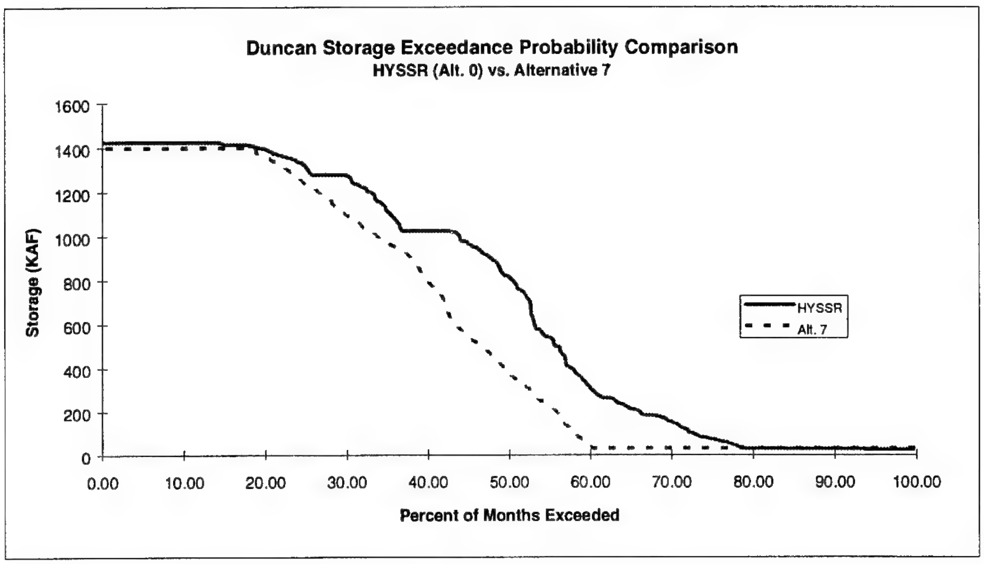


FIGURE 4.8 Comparison for Arrow Storage: HYSSR vs. Alt. 7





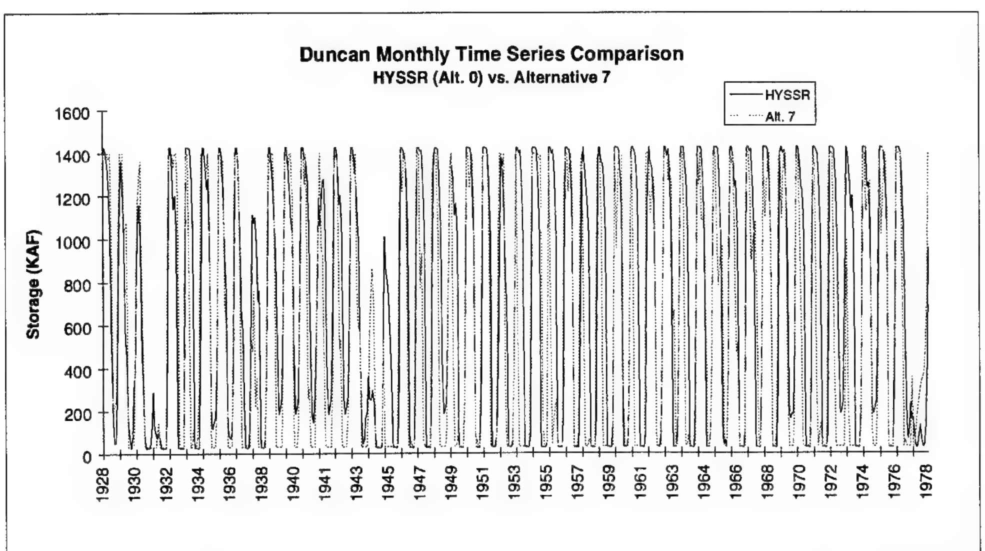
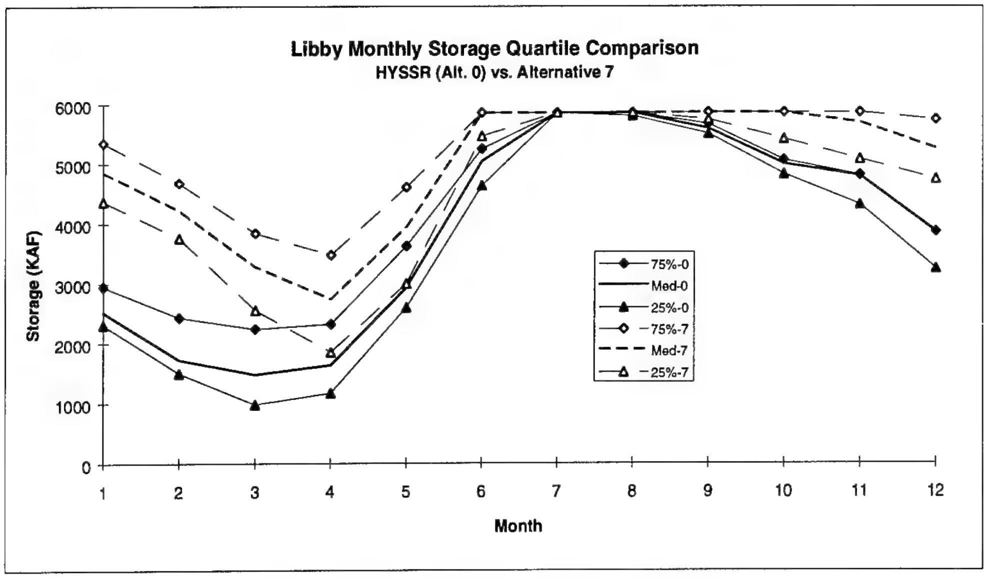
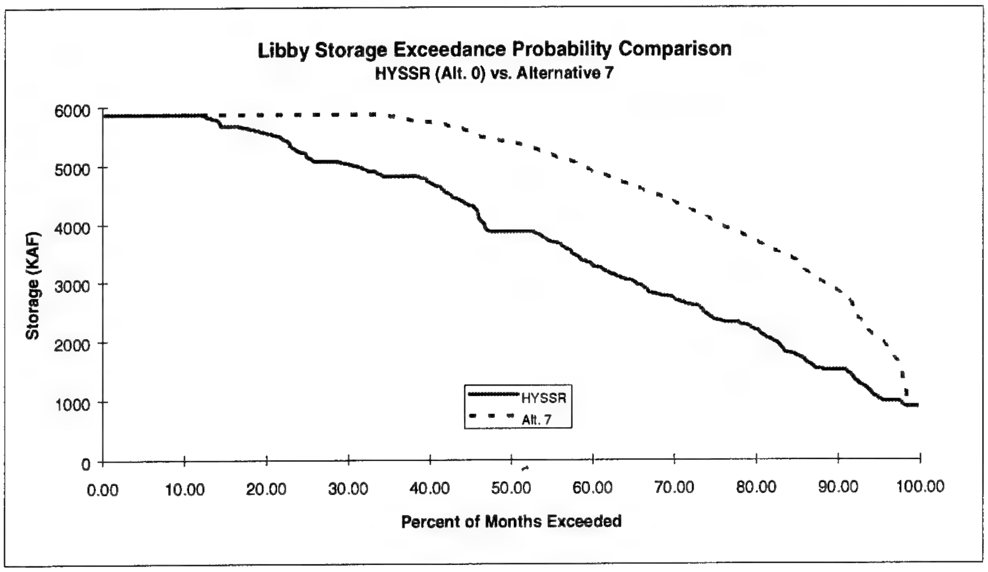


FIGURE 4.9 Comparison for Duncan Storage: HYSSR vs. Alt. 7





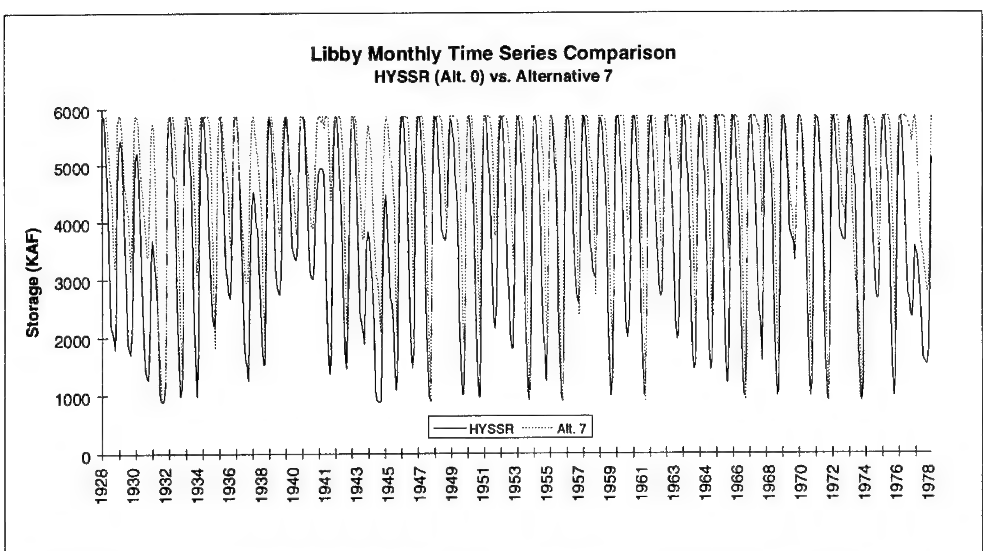
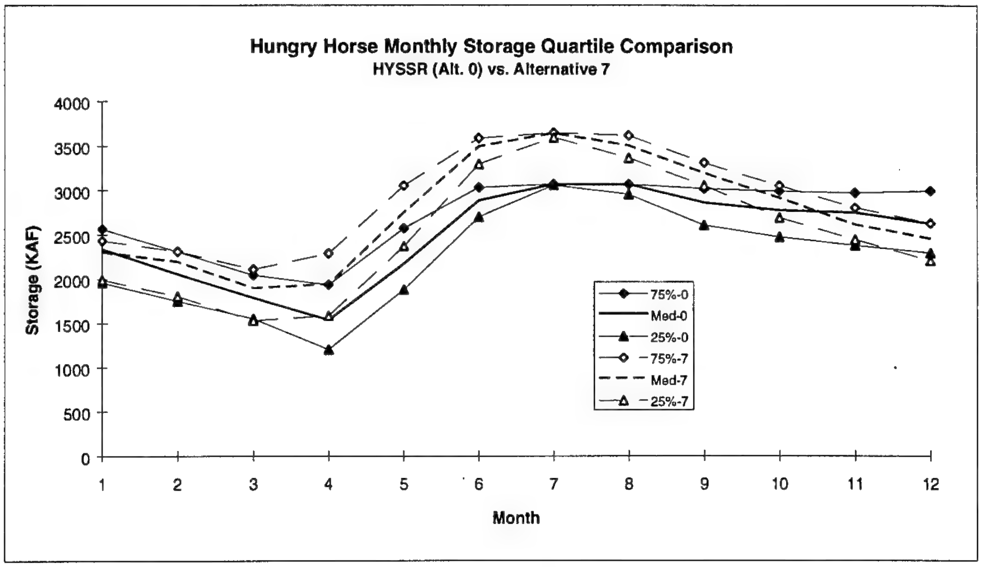
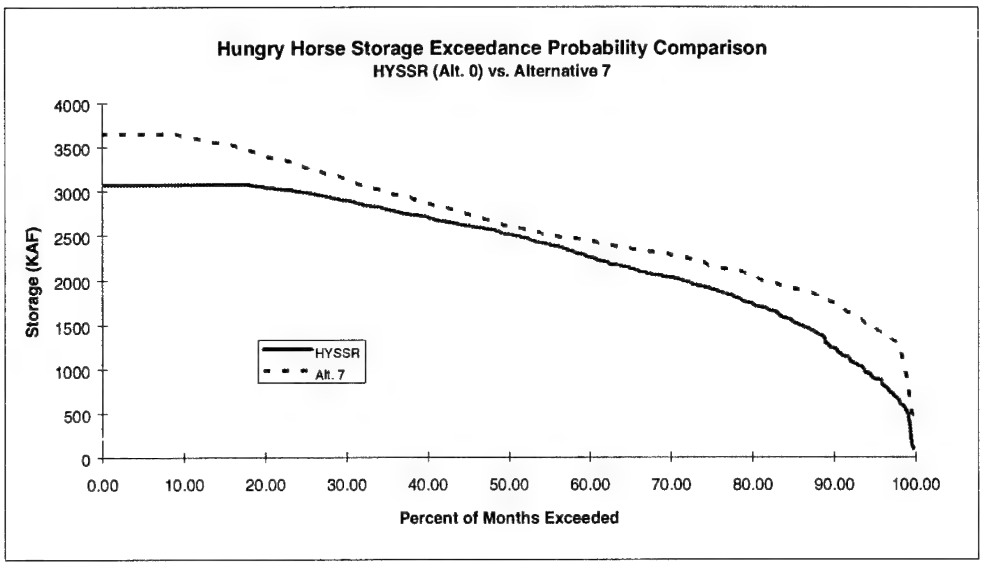


FIGURE 4.10 Comparison for Libby Storage: HYSSR vs. Alt. 7





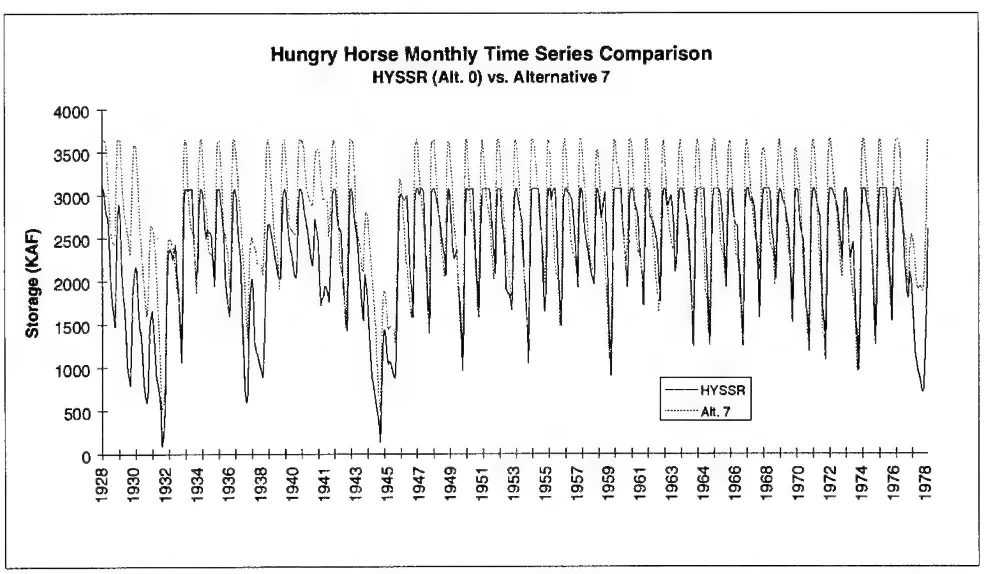
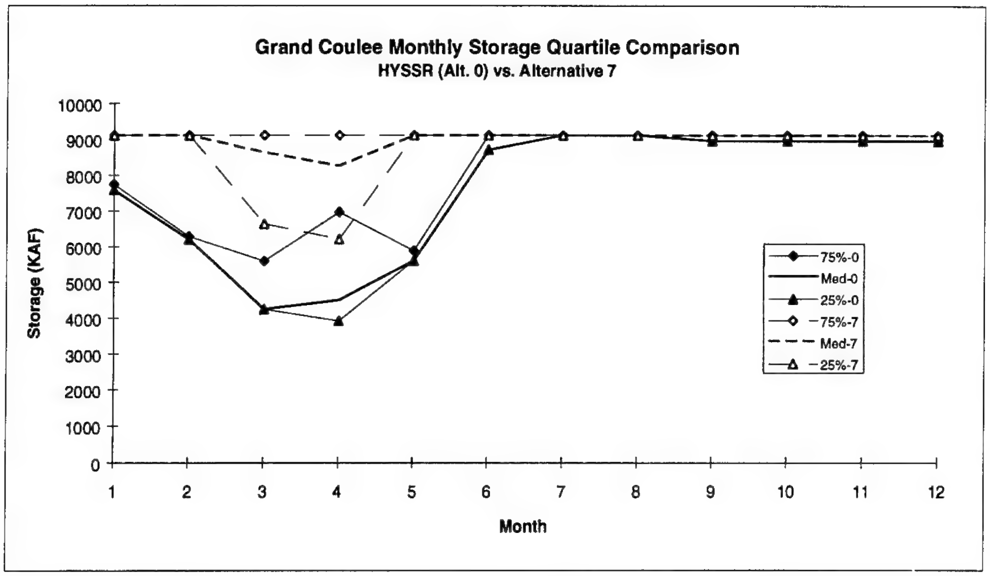
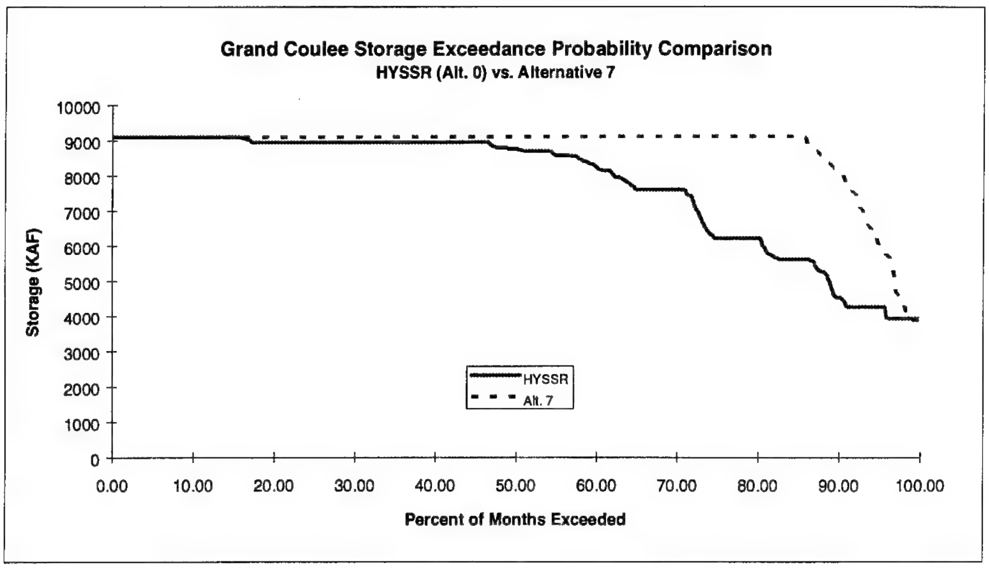


FIGURE 4.11 Comparison for Hungry Horse Storage: HYSSR vs. Alt. 7





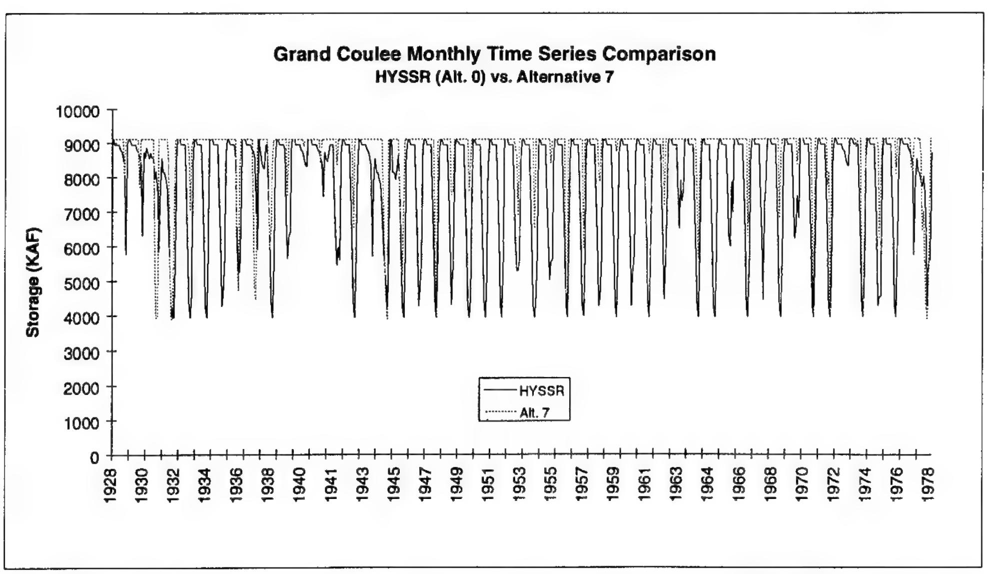
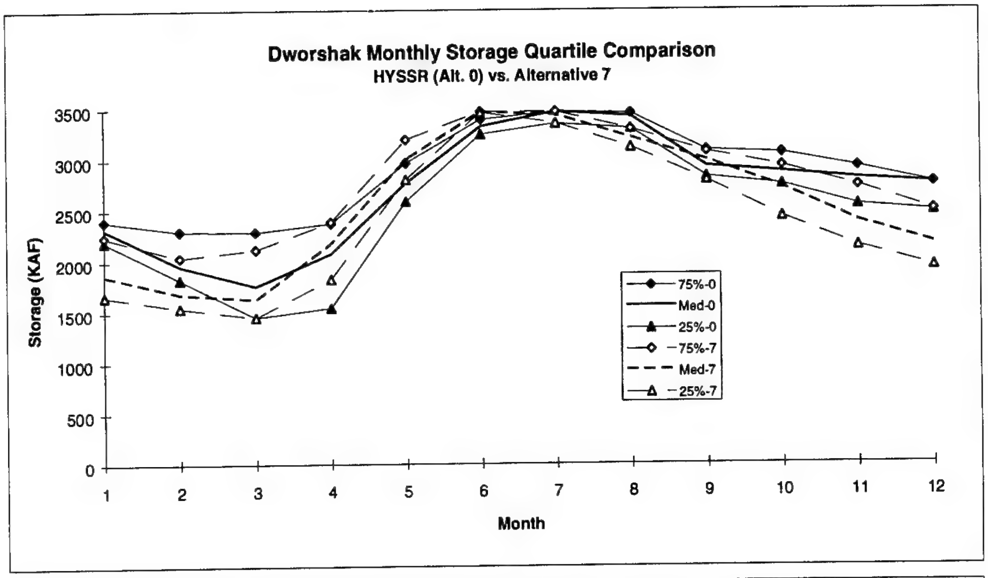
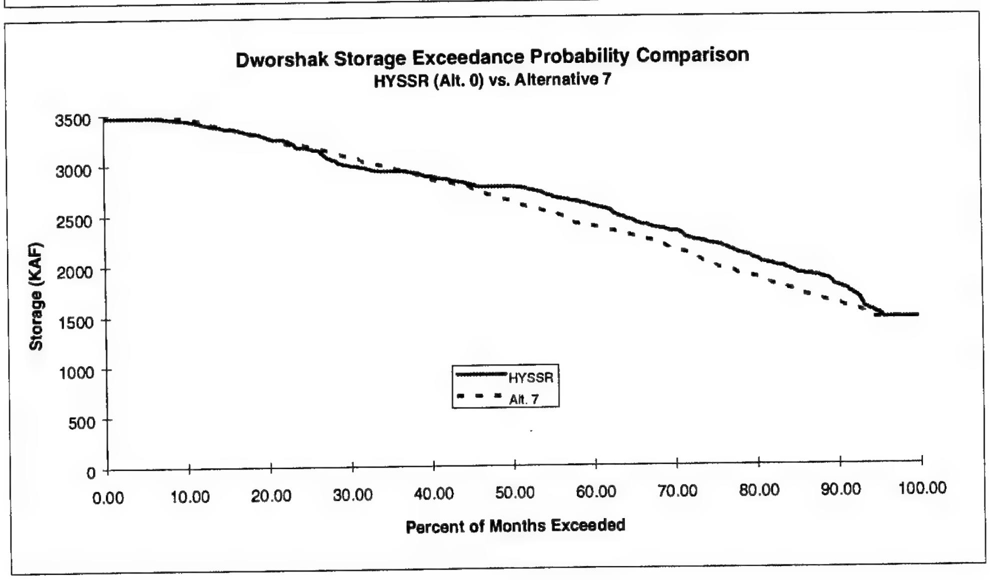


FIGURE 4.12 Comparison for Grand Coulee Storage: HYSSR vs. Alt. 7





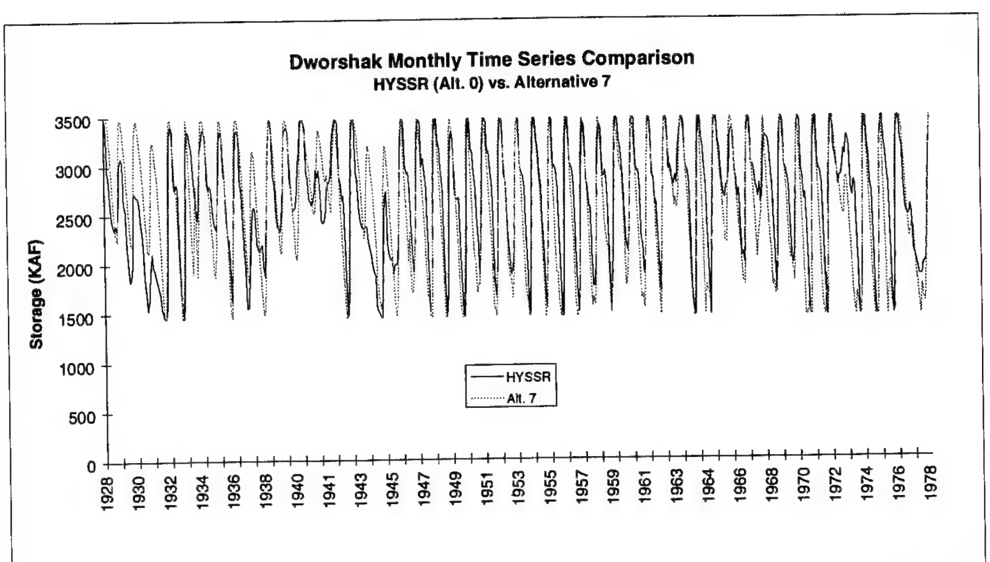
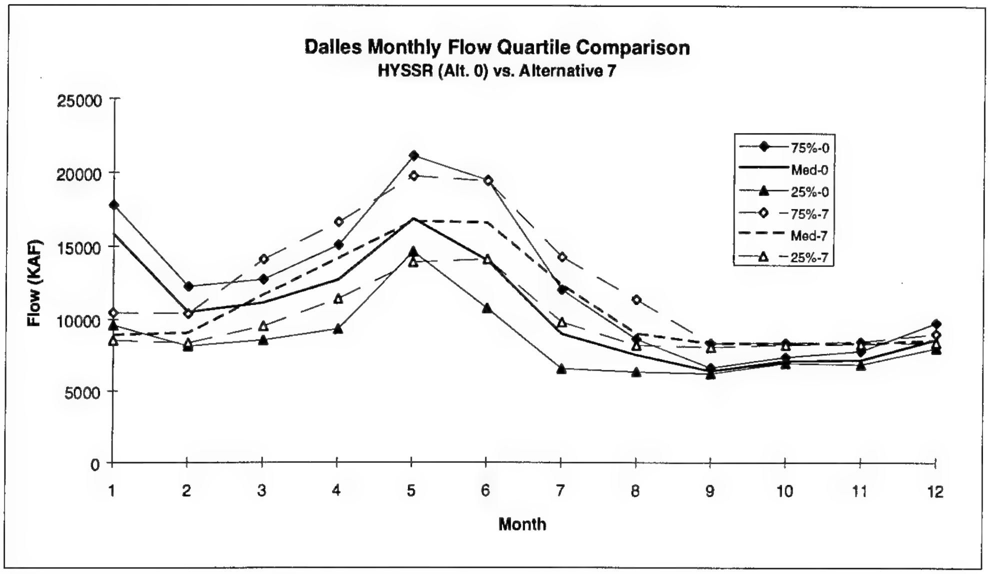
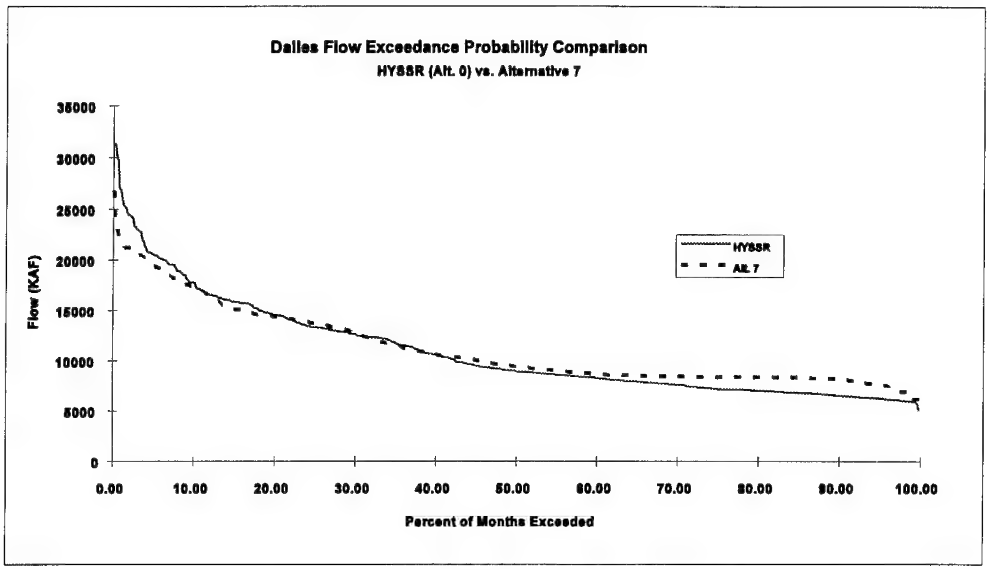


FIGURE 4.13 Comparison for Dworshak Storage: HYSSR vs. Alt. 7





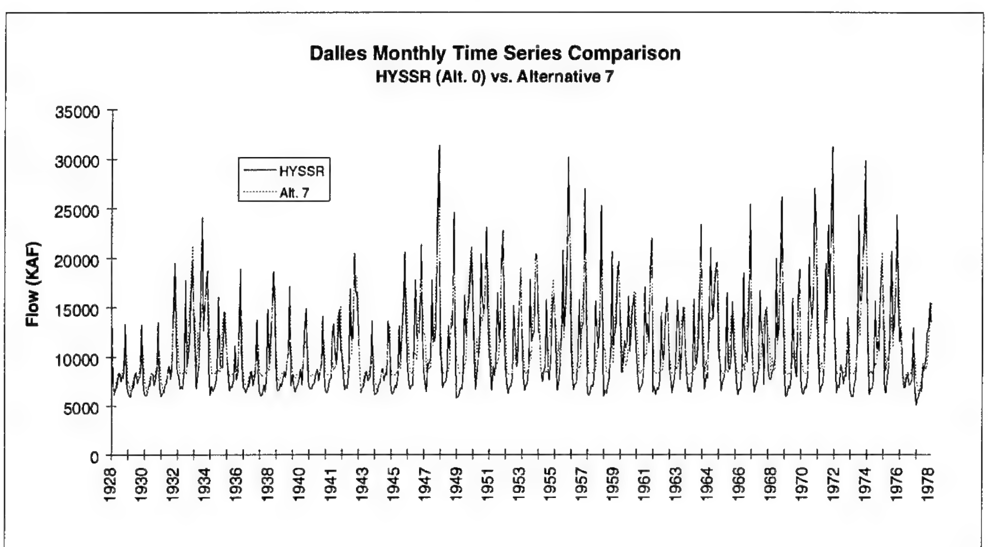


FIGURE 4.14 Comparison for Dalles Flow: HYSSR vs. Alt. 7

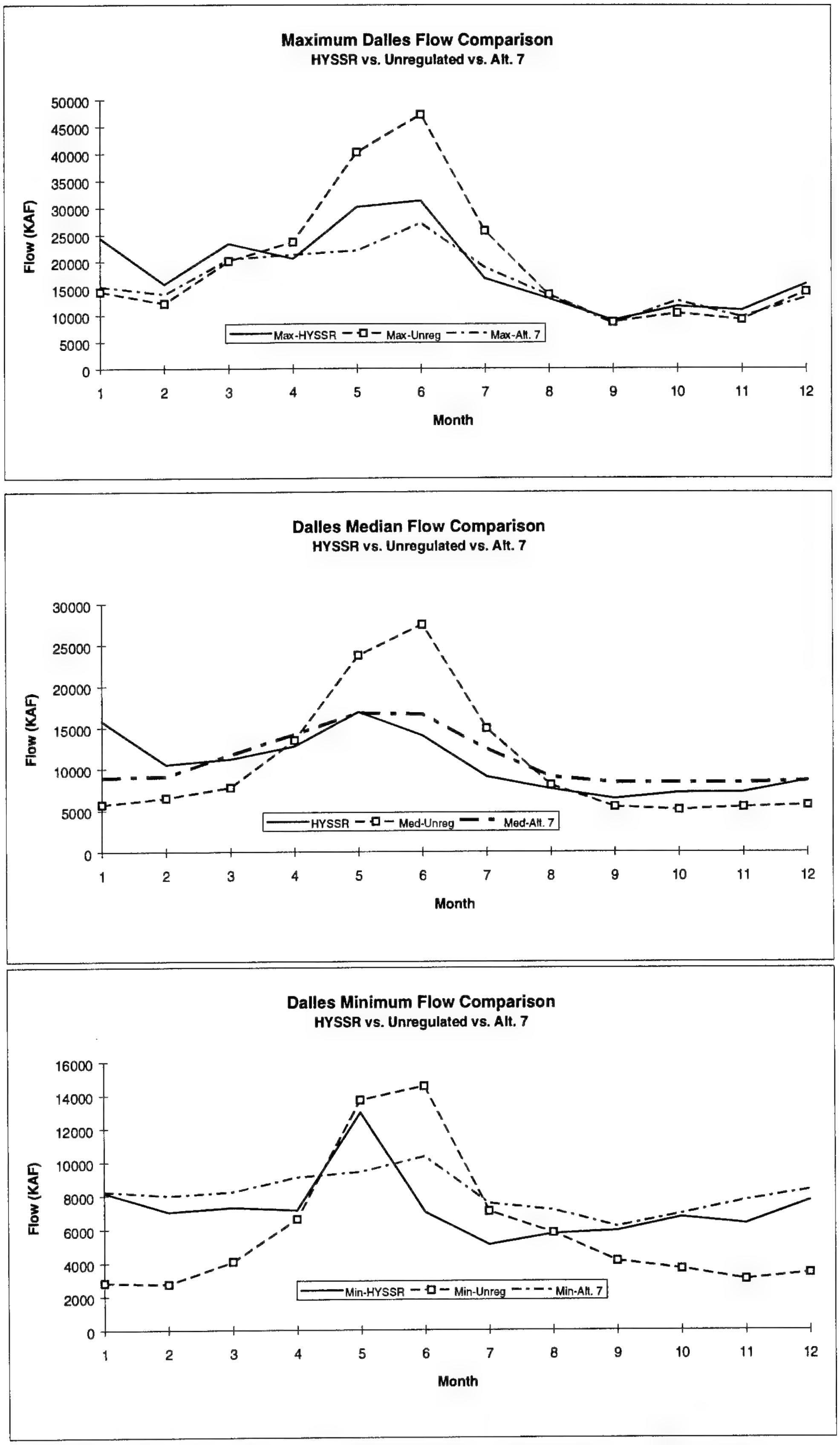


FIGURE 4.15 Quartile Comparisons for Dalles Flow: HYSSR vs. Unregulated vs. Alt. 7

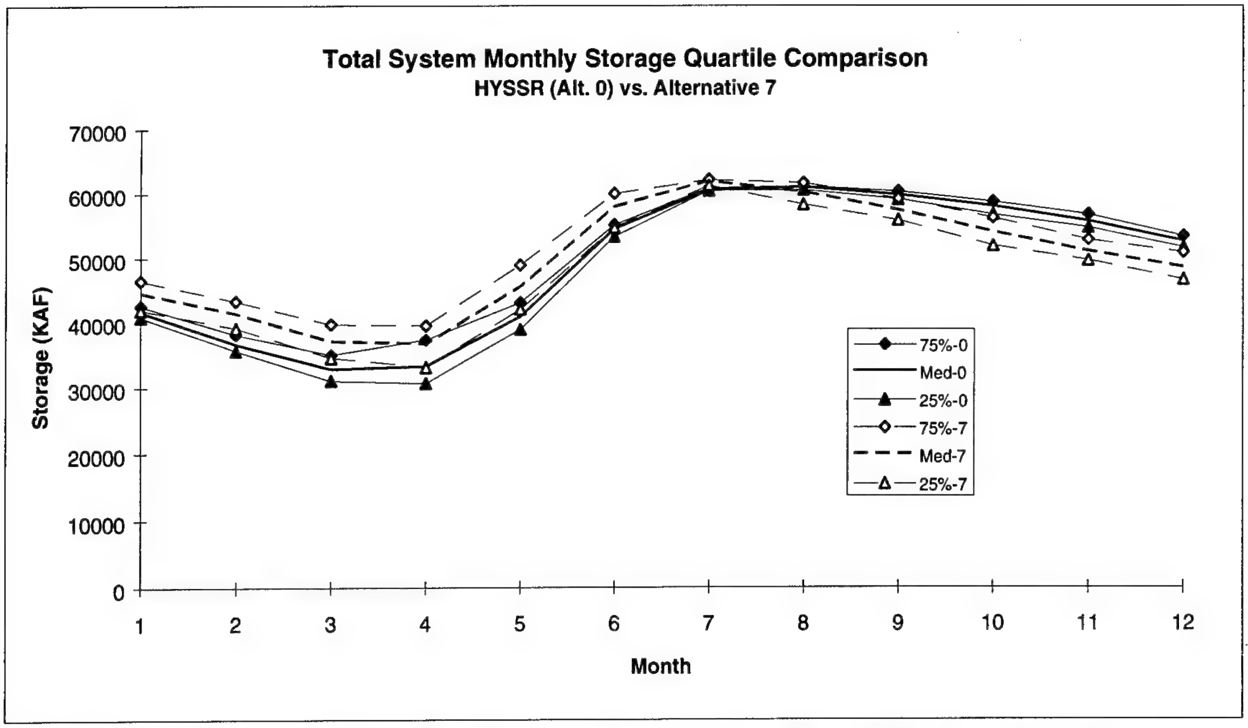


FIGURE 4.16 Comparison of Total System Storage Quartiles: HYSSR vs. Alt. 7

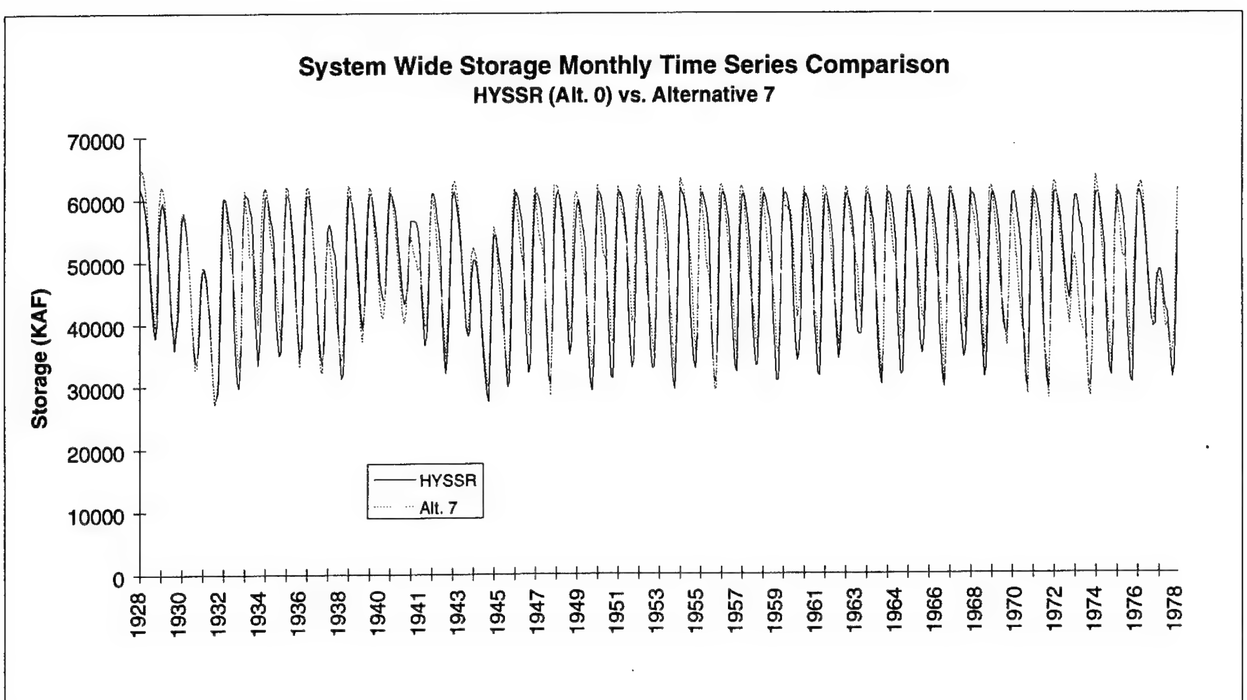


FIGURE 4.17 Comparison of System Wide Storage Time Series: HYSSR vs. Alt. 7

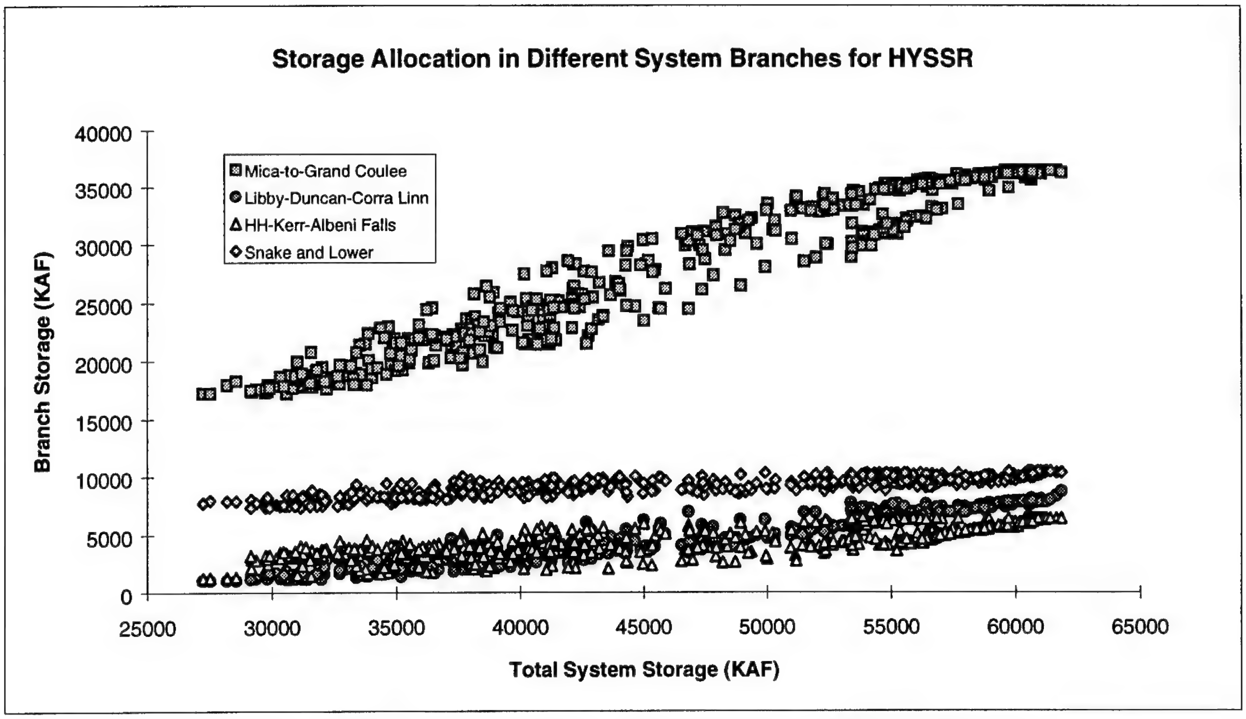


FIGURE 4.18 Storage Allocation for System Branches from HYSSR Results

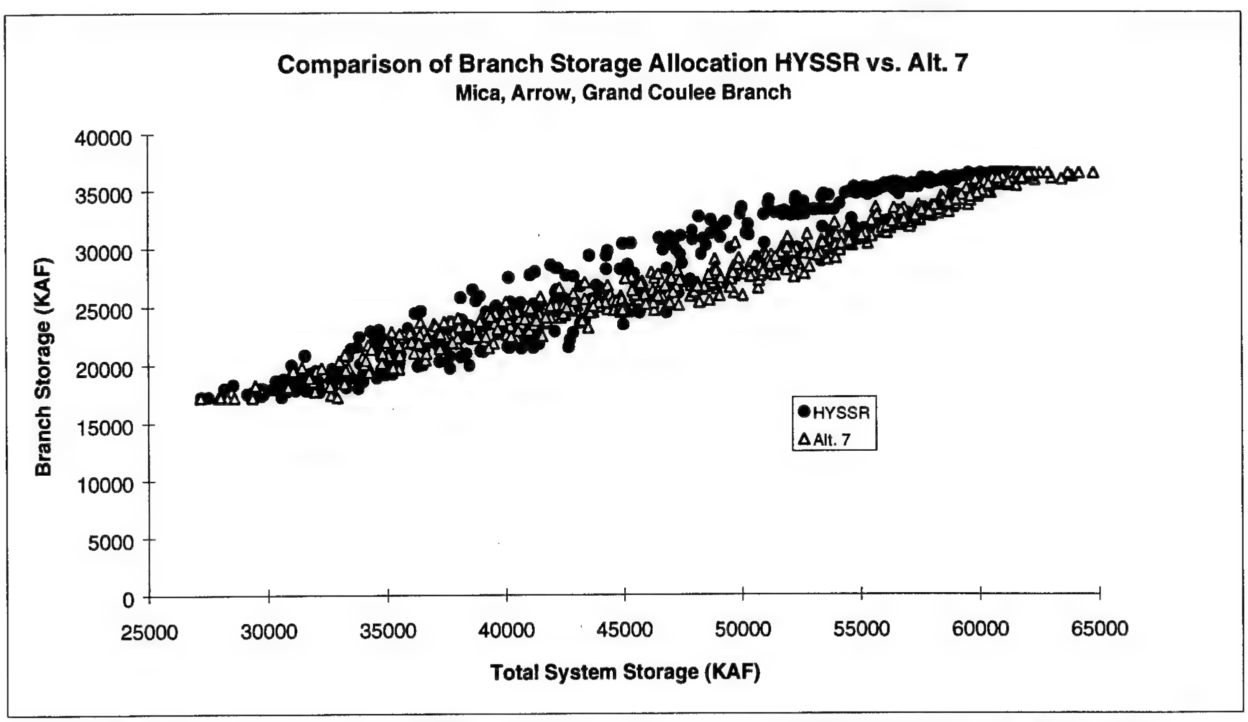


FIGURE 4.19 Comparison of Mica, Arrow, Grand Coulee Branch Storage Allocation

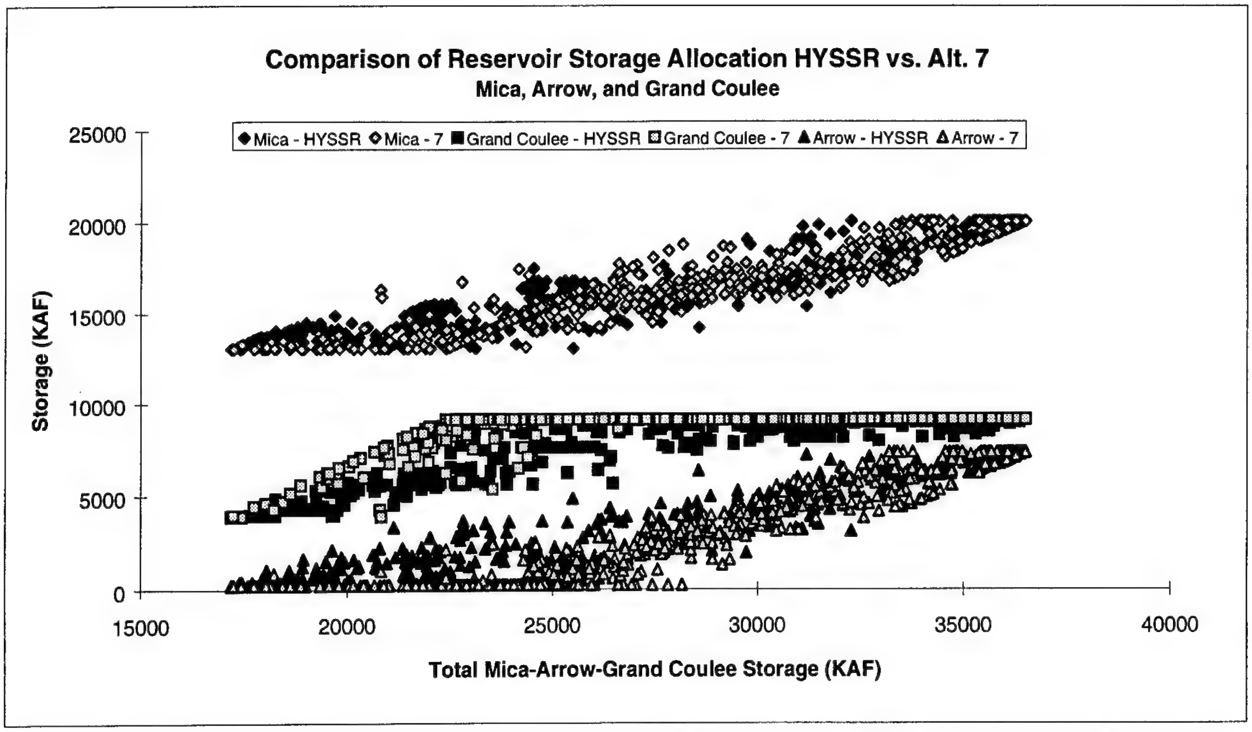


FIGURE 4.20 Comparison of Reservoir Storage Allocation for Mica, Arrow and Grand Coulee

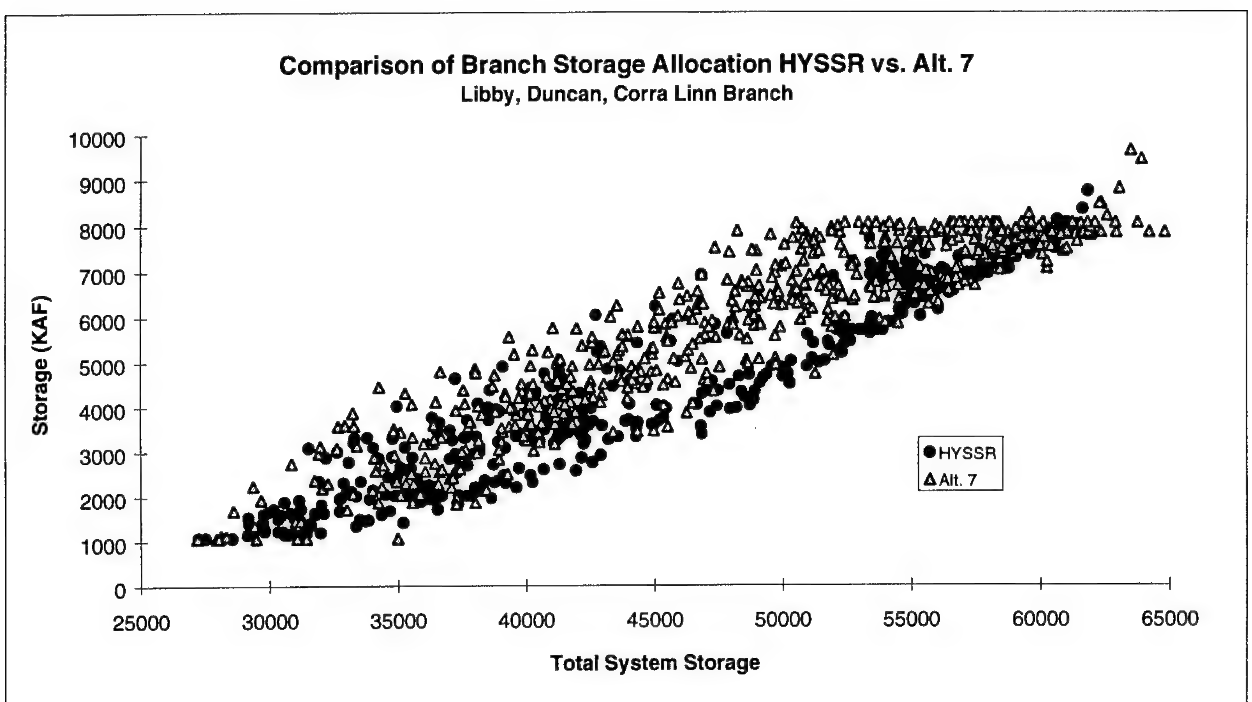


FIGURE 4.21 Comparison of Branch Storage Allocation for the Libby, Duncan, Corra Linn Branch

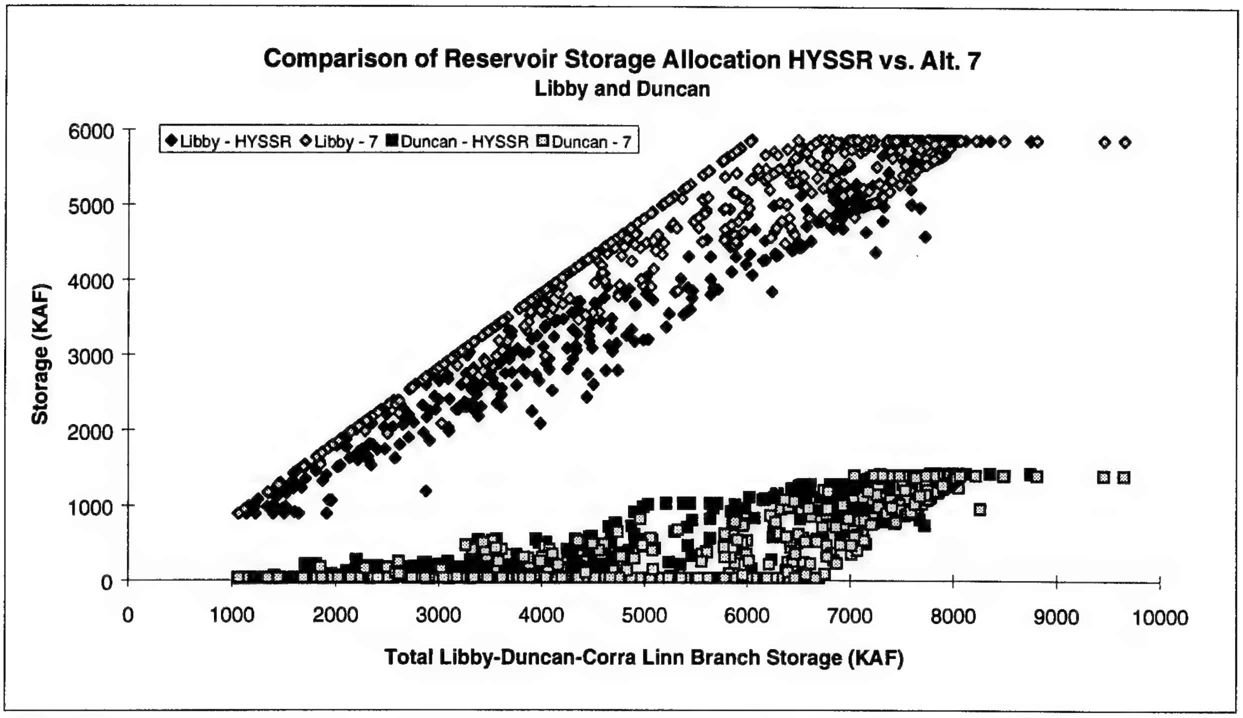


FIGURE 4.22 Comparison of Reservoir Storage Allocation for Libby and Duncan

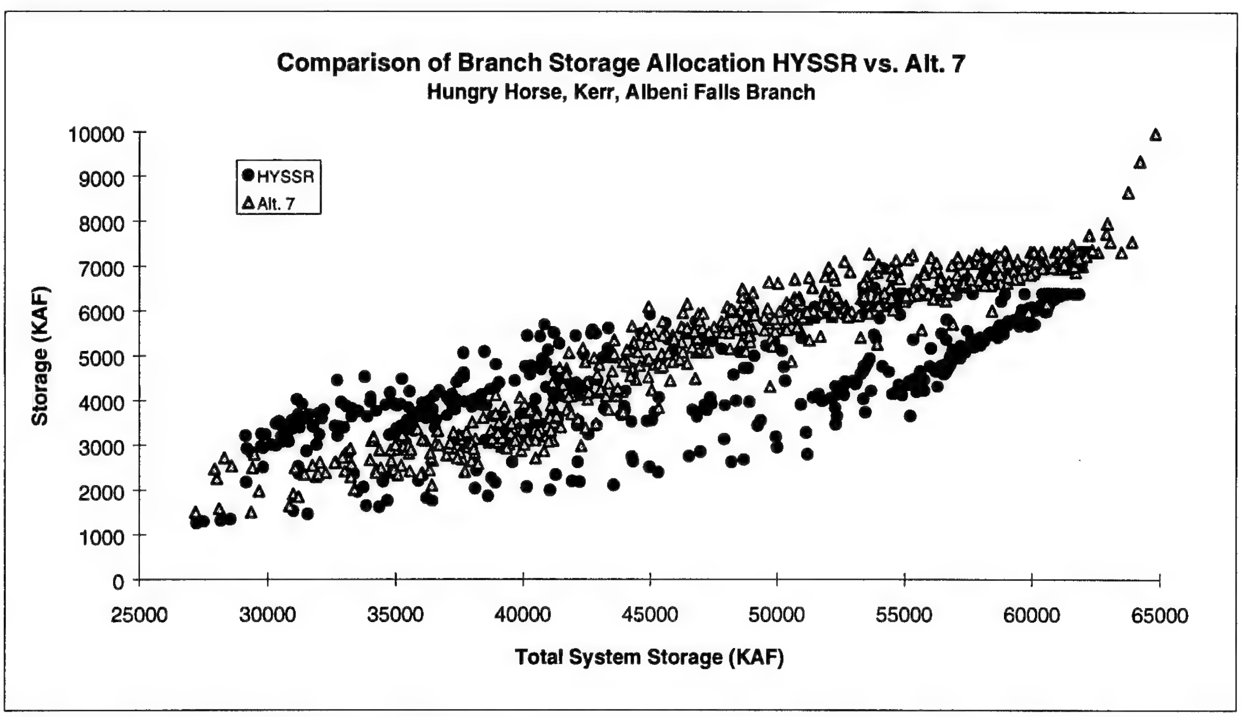


FIGURE 4.23 Comparison of Storage Allocation for Hungry Horse, Kerr, Albeni Falls Branch

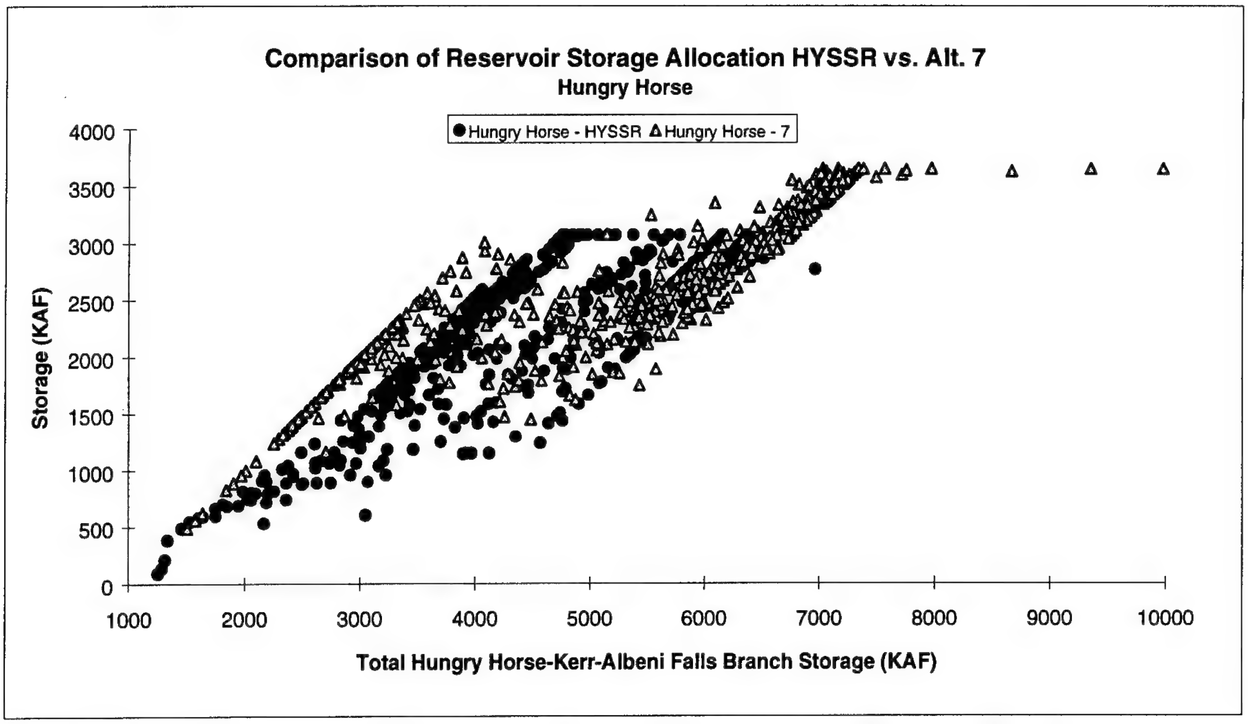


FIGURE 4.24 Comparison of Reservoir Storage Allocation for Hungry Horse

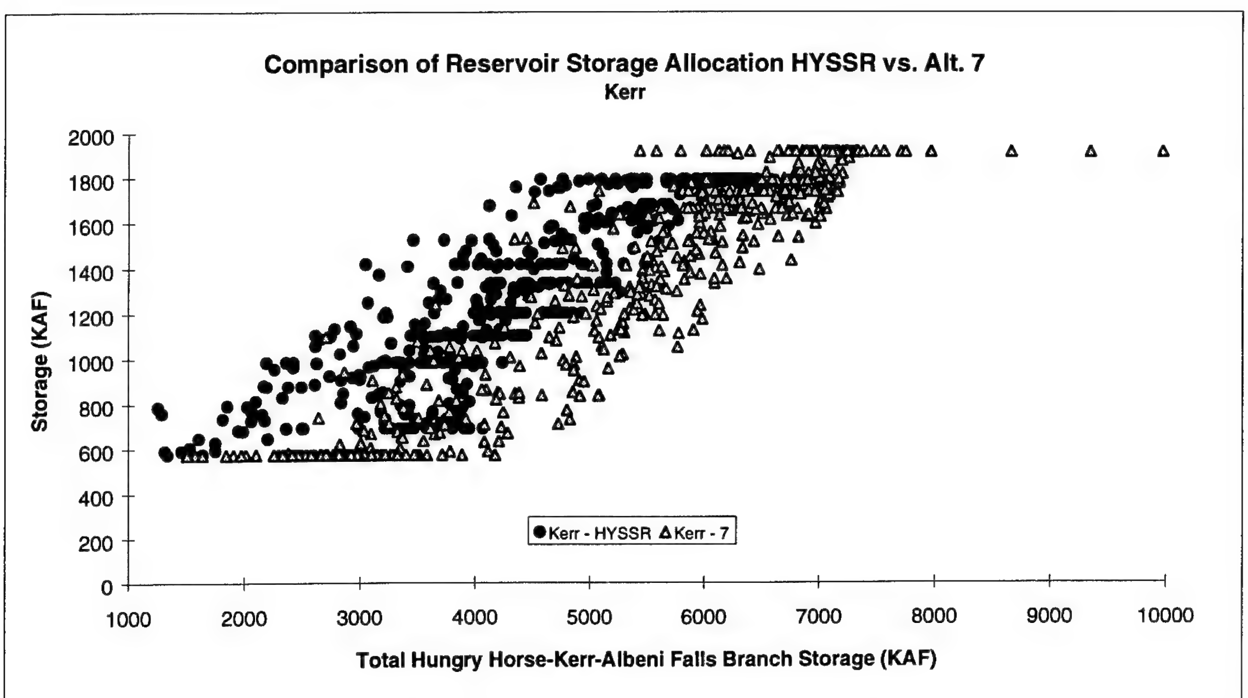


FIGURE 4.25 Comparison of Reservoir Storage Allocation for Kerr

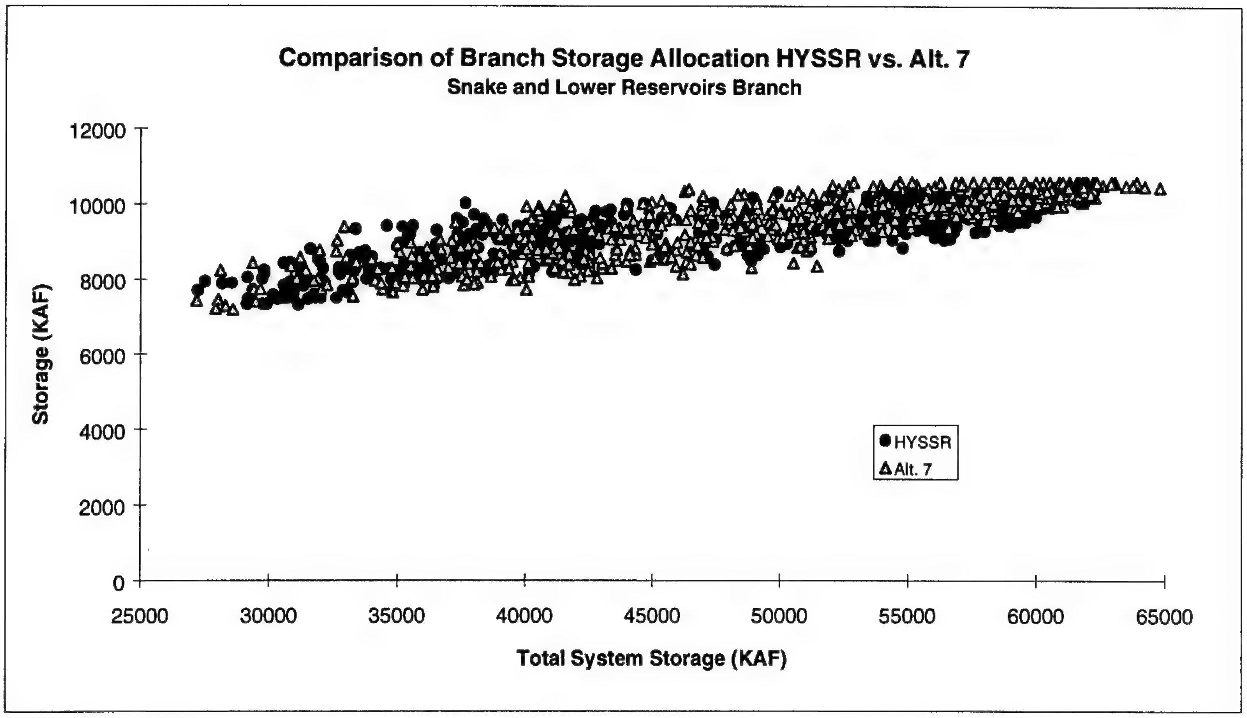


FIGURE 4.26 Comparison of Branch Storage Allocation for the Snake and Lower Reservoirs Branch

Chapter 5

System Operating Rule Suggestions from HEC-PRM Results

5.1 Introduction

Suggestions for changes in Columbia River system operations can be made based on the results presented in Chapters 3 and 4. In only a few cases are these suggestions great departures from current system operations, as represented by HYSSR operations. The suggestions are preliminary. Significant refinement and testing is needed before these suggestions could be implemented. In most cases, this refinement and testing process is most appropriately done by simulation modeling, probably through the use of HYSSR and other local Columbia River System models.

Approaches to Developing Operating Rules from Optimization Model Results

Approaches for developing operating rules from HEC-PRM are described in Appendix B. Two approaches are: (1) developing a set of operating rules "from scratch," ignoring existing operation procedures, and (2) suggesting modifications to existing operation procedures.

Where operation differs structurally and significantly from current operations, the optimization-based operating rules must be developed "from scratch." Developing rules "from scratch" requires a theoretically sound conceptual bases for operating rules which fits the pattern of operations in the optimization results. This is a difficult task for large multi-reservoir systems, operated for multiple objectives, with inflow hydrologies which can vary significantly from year to year. This approach was taken for preliminary operating rule development for the Missouri River system from HEC-PRM results (USACE, 1992; USACE, 1994b).

Where results of HEC-PRM demonstrate similarity to current operations, it is attractive to suggest modifications to existing operations based on the most significant differences between "optimized" and current operations. This approach should yield operation procedures which are more easily incorporated into system operations.

The second approach of suggesting modifications to existing system operations is the approach taken here for the Columbia River System. HEC-PRM's operation of the Columbia River System is structurally similar to current operations, represented by HYSSR results. The best illustration of this is the time-series comparison of total system storage results in Figure 4.17. Here, operation by HEC-PRM and HYSSR are nearly identical in terms of system-wide drawdown-refill amplitude and system refill. Drawdown rates are slightly different, with HEC-PRM drawing the system down a little sooner in the year. Operation of most individual reservoirs is also very similar between HEC-PRM and HYSSR. Still, some suggestions can be made based on differences in HEC-PRM and HYSSR results.

5.2 Potential Modifications to Current Operations

The presentation of potential modifications to current operations is organized by reservoir, with sub-headings by general type of operations, relatively constant pool operations, highly regulated and regularly varying operations, and major storage reservoirs.

John Day, McNary, and Granite

John Day is operated by HEC-PRM as a run-of-river facility with rare exceptions. These exceptions (Figure 3.1) tend to occur in drought and flood years. Reductions in John Day pools during drought years may be due to the steep penalty placed at The Dalles for representing system-wide hydropower. John Day results for Alternative 1 in the Phase II HEC-PRM application to the Columbia River System showed small John Day drawdowns only during flood years. The suggested modification would be to examine John Day operation as a run-of-river facility with possible exceptions during major flood events.

Both McNary and Granite are currently operated as run-of-river facilities. HEC-PRM operations (Figures 3.2 and 3.3) show greater seasonal and episodic variation for both reservoirs. McNary is drawn down to its lowest allowable level about 10% of the time under HEC-PRM and remains full about 65% of the time. HEC-PRM operation keeps Granite full about 85% of the time. Drawdown for both tends to occur early in the year with complete refill always in July. The suggestion is that seasonal or other episodic operations be examined for McNary and Granite reservoirs. However, given the relatively small operating range of these reservoirs there is not likely to be a great economic impact from their more flexible operation.

Albeni Falls, Kerr, and Corra Linn

Albeni Falls operation is regular under both HEC-PRM and HYSSR (Figure 4.4). HEC-PRM operations tend to keep Albeni Falls full longer than HYSSR, with steeper drawdown and refill. This modified regular operation is suggested for further examination.

Kerr's operation is more similar between HEC-PRM and HYSSR (Figure 4.5). Under HEC-PRM, drawdown is delayed slightly and refill occurs more quickly. A higher full pool level is also suggested. These small changes might merit additional examination.

Corra Linn's operation by HEC-PRM has penalty functions intended to reflect International Joint Commission-specified operations. Nevertheless, there are some differences between HYSSR and HEC-PRM operation of Corra Linn (Figure 4.6). Typically, HEC-PRM draws Corra Linn down about 2 months earlier in the year and begins refill a little later. These differences might be usefully studied.

Major Storage Reservoirs

Mica operation by HEC-PRM is similar to HYSSR except for an earlier beginning of drawdown (Figure 4.7). This is the only major difference and is suggested for further study.

HEC-PRM draws both Arrow and Duncan down earlier in the water year and is less likely to refill during drought years (Figures 4.8 and 4.9). However, the drawdown rate on Arrow and Duncan varies greatly from year to year. This results from HEC-PRM operating Arrow and Duncan as unfettered storage for keeping Grand Coulee full. This increased operation of Arrow and Duncan, tied to operation of Grand Coulee, is strongly suggested for further examination.

Libby's operation under HEC-PRM has a later and usually smaller seasonal drawdown, with slightly earlier refill (Figure 4.10). Some of this may result from the more significant operation of Duncan. This modified operation of Libby is suggested for further examination.

Hungry Horse operation under HEC-PRM is similar to HYSSR (Figure 4.11) except that Hungry Horse refills to a greater storage level and draws down to an almost equally greater maximum drawdown level. This difference is explained by the use of a dated storage-elevation table in the specification of the HEC-PRM model. This results in the HEC-PRM model having roughly an additional 500 KAF of storage capacity at Hungry Horse than is represented in the HYSSR model. When this difference is removed, HEC-PRM and HYSSR operation of Hungry Horse should become more similar.

Grand Coulee operation under HEC-PRM is significantly different than under current practice (Figure 4.12). In most years, HEC-PRM operation draws down Grand Coulee only slightly and for short periods of time. Significant drawdown of Grand Coulee under HEC-PRM only occurs during drought and in anticipation of floods. Under HEC-PRM, Grand Coulee is full over 85% of the time. This absence of significant yearly drawdown by HEC-PRM is partially a result of HEC-PRM's foresight of floods. Still, the results strongly suggest further examination of reducing Grand Coulee drawdowns to gain additional hydropower and other benefits compared to increased potential for flood damage.

Dworshak operations in HEC-PRM are similar to those of HYSSR, except drawdown tends to be more rapid in late fall and refill slightly faster (Figure 4.13). Drought operation of Dworshak appears to differ more significantly from that of HYSSR, with a greater tendency to refill.

5.3 Refinement and Testing of Operating Rule Suggestions

The suggestions for modifications to current operating rules are preliminary. Such suggestions require refinement and testing by simulation modeling. Such simulation can better tune these suggestions to the system. Simulation modeling can also better evaluate the effectiveness of modified rules on system operating objectives compared with current operations.

5.4 Conclusions

Some modifications to current operating rules are suggested by the HEC-PRM model of the Columbia River System. With the exception of suggestions for modifying the operation of Grand Coulee, Arrow, and Duncan, they are relatively small changes compared to current operations. However, for such a large system with net benefits measured in billions of dollars per year, the effects of even small changes can be considerable in absolute terms. The suggestions for operation rule modifications are preliminary. They require refinement, testing, and evaluation by more detailed simulation modeling.

Chapter 6

Potential Annual Operations Use of HEC-PRM

6.1 General

This chapter presents an approach for using HEC-PRM to aid in annual operation of the Columbia River System. It uses a number (3-50) of short (1-5 year) HEC-PRM runs to help select promising operations for individual reservoirs in the Columbia River System. This type of approach has been used successfully elsewhere. An example application is presented.

6.2 Introduction

Operations planning is characterized by uncertainty in future stream flows. The problem of operations planning then becomes one of suggesting operation rules which are likely to meet system objectives. In the case of the Columbia River System, this entails maximization of hydropower, recreation, irrigation, fisheries, and flood control values, with reasonably prudent operations to consider potential flood and drought conditions.

There have been several real and academic applications of optimization for short-term reservoir operations. Applications similar to that suggested here for the Columbia River System exist elsewhere (Crawley and Dandy, 1993; Palmer and Tull, 1987; Palmer and Holmes, 1988; Croley, 1974). The approach suggested here extends earlier work applying simulation modeling for operation planning and risk analysis for annual and seasonal time frames (Hirsch, 1978, 1981a, 1981b) and to drought management in the Washington, D.C. region (Sheer, 1980).

The current annual operating year for the Columbia River System runs from August through July. In August, current storage levels and forecast power demands are submitted by the different agencies involved with the system. Operating rule curves are then derived by simulation for each reservoir.

The August to December period is characterized by relatively predictable inflows. Thus, during this period reservoir operations are essentially fixed, based on the developed rule curves. During the period from January until July, flows are more variable, with forecasts of runoff made periodically. These forecasts are used to update reservoir operating rule curves. Rule curves are also modified to accommodate short-term energy demand forecasts.

The approach presented is relevant to the updating of operating rules during the January-July period, but might also be used during the August-December period.

6.3 Outline of Approach

The approach uses HEC-PRM to suggest desirable operations for a variety of plausible future stream flow conditions based on historical stream flow and forecast records. The range and distribution of HEC-PRM-suggested storage and release decisions can then be used in the development of monthly storage and release targets for individual reservoirs throughout the system. This approach has four steps:

Step 1: Set up the problem for HEC-PRM.

In this step, the system is defined relevant to the operation problem and compatible with HEC-PRM. In addition to the normal system specification (USACE, 1993), operation problem applications also require:

a. setting initial reservoir storages at current levels,
b. updating penalty functions for near-term conditions, and
c. setting fixed values or penalty functions for end-of-analysis period target storage levels in each reservoir. This step mostly establishes current reservoir conditions and establishes the objectives, represented by penalty functions, for system operation.

Step 2: Select appropriate potential future inflow hydrologies.

Here, the number, duration, and particular years of historical inflow hydrology are selected. These years of record might represent extreme conditions (critical period or extreme flood) or a range of years representative of current snowpack and climatic conditions. Or, as is currently done for the Columbia River System simulations, historical inflow records may be modified to reflect current hydrologic conditions of snow-pack, other moisture conditions, and precipitation forecasts. Aspects of these selections are discussed in later sections.

Step 3: Solve the HEC-PRM model for the designated inflow hydrologies.

This step requires extensive data management and computer operations decisions to use effectively the input and output data for the many runs needed.

Step 4: Incorporate results into larger operations planning process.

HEC-PRM results are not used directly to operate reservoirs. Instead, HEC-PRM can provide suggestions and analytical support for existing operations planning activities. These can take several forms:

a. Suggestion of a range of desirable short-term operating decisions.
b. Use in defining annual operating rules for individual reservoirs.
c. Estimation of power yields for the system in rough probabilistic terms, for use in estimating firm, and secondary power yields and their likely availability over time.

The remainder of this chapter discusses some details of this approach and an example application to the Columbia River System for January-July 1994. Most of the details discussed here are not yet resolved conclusively and the example results are preliminary.

6.4 Some Technical Issues for Seasonal Operating Studies

Technical issues for conducting seasonal operating studies using HEC-PRM are presented in this section. Most of these details are not resolved conclusively, and their appropriate resolution might vary with the particular study being undertaken.

Final Period Storage Targets

A HEC-PRM model will typically drain the system to create additional hydropower and flow benefits without some constraint or penalty based on end-of-analysis reservoir storage. Handling of end-of-analysis period storages is therefore required. Several options exist for establishing final storage targets:

a. Each reservoir storage level could be fixed for the final time period for all runs. This assumes the end condition period is know for all reservoirs. While easy to implement, it may not represent well desirable operation where over-year storage exists and may reduce the ability to move storage about different reservoirs in the system.

b. Each end-period reservoir storage level could be fixed, but this target level could vary for each hydrologic condition examined. Dry years might have different targets than wet years, for instance. The setting of these targets for each year and reservoir could be done by experienced engineers or perhaps by a longer-term HEC-PRM run.

c. A different approach would be to develop a penalty function for each reservoir's storage at the end-of-analysis period. Such a penalty function might be developed via long-term simulation or HEC-PRM analysis. Alternatively, for systems with relatively little over-year storage, such as the Columbia River System, the value of storage at the end of the analysis period can be estimated directly from the functions of the stored water, such as the value of the energy stored in the reservoir for use during the fall and winter months.

The HEC-PRM program has been modified to accept special storage penalty functions for the end-of-analysis period (USACE, 1994a). Different solutions to this problem might be preferable for different systems and different years. During wet years for systems with little over-year storage, constraining ending storages to target levels is probably best.

Selecting an Analysis Period Length

The length of analysis period for each HEC-PRM run should be long enough to capture the importance of future inflows for near-term operations, but not so long as to provide too much foresight into the coming year's operation, such as for operation to accommodate major floods or droughts in the coming year. The selection of an analysis period for annual operations must be

based on the characteristics of the particular reservoir system. In the case of the Columbia River System, where the critical period is but four years long and refill of system storage is common, analysis periods from one to four years seem appropriate. A shorter analysis period might also make sense, since most system drawdown and refill occurs between January and July.

The selection of an analysis period is also linked to how targets for end-of-analysis period storages are handled. Where end-of-analysis storage targets are fixed, longer analysis periods might be desirable, particularly for years when the system refills. Where end-of-analysis storage targets are represented as penalty functions, the problem formulation has greater flexibility, allowing shorter analysis periods to be used.

For this exploratory application to the Columbia River System, January to July (7 month) analysis periods are used.

Selecting Hydrologic Inputs Based on Runoff Forecasts

Starting January 1, forecasts of January-July runoff volumes become available, and are updated periodically throughout the high-runoff season. These runoff forecasts form a useful basis for selecting representative hydrologies for HEC-PRM runs. Two approaches were considered for employing these forecasts with historical inflow records.

The first approach employs a current runoff forecast with the forecast and actual runoff values for historical inflow records to estimate different weights for each historical year's inflow record. Past years with forecast and actual inflows similar to the current year's forecast would be weighted more highly than past years flows with dissimilar forecast and actual runoff values. This approach is described below.

Figure 6.1 shows the performance of January 1 predictions of January-July runoff above The Dalles. Each observation represents predicted vs. actual runoff for one year from the historical record. These forecasts provide a guide to whether the coming season is likely to be wet or dry. They are not perfect. The forecasts also do not give a good idea as to when and where the runoff is likely to occur. However, these forecasts might serve in selecting a sub-set of annual hydrologies from the historical record, which are consistent with the forecast.

This approach would seem to provide a reasonable role for forecast information in HEC-PRM runs used for annual operation planning without overemphasizing the accuracy of forecast information. The approach also provides a rough probabilistic basis for the timing and spatial distribution of inflows into the system over the annual operating period. Appendix E describes quantitative approaches for assessing relative weights to inflow records of different years from the historical record. However, this approach was found to be too unstable for application here.

A second approach, chosen for the example, more closely follows current simulation modeling practice for the Columbia River System. For this system, starting January 1, runoff forecasts are made periodically for points throughout the basin. One use of these forecasts has been as a basis for modifying historical stream flow records to reflect what those flows are likely to have been had basin conditions been as they are at the beginning of the current forecast period.

This approach is more labor and expertise intensive than the first approach considered, but brings a greater amount of information to bear on the analysis. The result, presumably, is modified annual inflow records which are equally likely.

6.5 Seasonal Operation Study Results and Their Uses

The results of seasonal operating studies using HEC-PRM are discussed in general terms below. The presentation of uses of such results are of particular concern.

Traces of Storages and Flows

An example of results from this approach to using HEC-PRM results is shown for storage in an individual reservoir on Figure 6.2. Each storage trace is the result of a single HEC-PRM run, using a different potential inflow hydrology and with the same initial storage conditions. While these traces are plots of raw HEC-PRM output, they do tend to indicate the range and trends in storage conditions that can be expected in the reservoir over the coming year. Similar trace plots can be created for reservoir releases, channel flows, and system-wide hydropower generation. Potential uses and refinements of these data are discussed in the following sections.

Probabilities of Storage Levels and Flows

The traces of storage and flow results from multiple HEC-PRM runs can be simplified into approximate probability distributions for each month during the operating period.

An example of such a frequency plot for reservoir storage levels is the exceedance probability plot on Figure 6.2. Figure 6.2 also contains a monthly quartile plot for reservoir storage, that expresses largely the same information in a different way. Such information might be useful for informing recreational users on the likelihood of low water elevations or flooding in the coming season. Similar plots for flows might be useful for assessing the risk of attaining fish flow targets.

Estimating Power and Water Supply Yields

The flow and storage results from each HEC-PRM run are used to produce monthly estimates of system-wide hydropower generation. For different representative future inflow conditions from the same starting storage conditions, these hydropower production estimates could be used to assess the likely firm, secondary, and incidental hydropower yields available on a monthly basis for the coming year. Employing releases and storages suggested by HEC-PRM as input to other existing hydropower simulation models would probably provide more detailed and accurate hydropower production estimates than direct use of less detailed HEC-PRM hydropower production calculations.

Suggestions for Near-Term Decisions

Particularly in the near-term, the release results from multiple HEC-PRM runs should be representative of optimal reservoir release decisions, based on current conditions. For periods when there is relatively little hydrologic variability (such as winter flows on the Columbia basin, there is likely to be great "consensus" in HEC-PRM results as to what near-term releases should be. For spring and summer snow-melt seasons, there is likely to be much greater scatter in releases suggested by HEC-PRM. Nevertheless, the results should serve to inform operators of the likely range and distribution of desirable reservoir releases.

Development of Annual Operating Rule Curves

Current operation of Columbia River System reservoirs is based on a set of rule curves developed from a suite of simulation model results. A similar set of operating rule curves could be developed from HEC-PRM results, probably with refinement using simulation modeling.

6.6 Example Application to January 1994 Conditions

The approach described here is applied to the year 1994, using 1928-1978 historical flow modified for January 1 runoff forecast information. The actual reservoir storages and January-July runoff forecasts at The Dalles for January 1994 appear in Table 6.1. The storage data are used as starting reservoir conditions for HEC-PRM runs.

North Pacific Division (NPD) personnel provided historical inflow records modified to incorporate January 1, 1994 estimates of January-July runoff volumes. This constituted the hydrologic inputs to the HEC-PRM model. Exceptions to this were inflows at Columbia Falls, Bonners Ferry, and Spalding locations, which are not usually estimated by NPD for seasonal HYSSR studies. For these locations, the unmodified 50-year record was employed. Releases from Brownlee used in the seasonal HEC-PRM analysis were also unmodified from the 50-year analysis. NPD staff also provided estimates of withdrawals from Grand Coulee reservoir for Bureau of Reclamation projects. These replaced estimates used in the long-term HEC-PRM runs. In other regards, the HEC-PRM model used for this example was the same as the long-term Alternative 7 runs. HYSSR output from long-term runs was also used to replace Brownlee reservoir operations for the system; this was the same representation of Brownlee as was used for the long-term HEC-PRM runs.

HEC-PRM runs were then made for each year from the historical record, with initial storages corresponding to actual January 1, 1994 storages. Each HEC-PRM run was seven months in length, running from January 1 until July 31 for each year. Presumably, each of the 47 inflow sets used is equally-likely.

Table 6.1
1994 Actual Storage Volumes and Runoff Forecasts for January-July Dalles Runoff

	Reservoir	January 1 Gross Storage (KAF)
	Mica	14,304
	Arrow	5064.9
	Duncan	24.2
	Libby	2426.6
	Corra Linn	817.0
	Hungry Horse	871.3
	Kerr	1039.7
	Albeni Falls	496.4
	Grand Coulee	8531.5
	Dworshak	1804.8
	Brownlee	1266.6*
	Granite	1825.0
	McNary	1300.0
	John Day	2297.1
Runoff Forecast (MAF) for January-July at The Dalles		80

* Brownlee operations are replaced by HYSSR results in the current HEC-PRM model.

Figures 6.2 through 6.6 show selected results of this analysis for storage at Arrow, Mica, Grand Coulee, Dworshak, and flow at The Dalles. For Arrow (Figure 6.2) results suggest the desirability of an early drawdown, likely to be complete by the end of February, with refill beginning before the end of May and ending in June or July, depending on inflow conditions. The exceedance probability plot gives the probability of the reservoir refilling to different levels and the probability of different reservoir levels (in storage units) for different months. Mica operation (Figure 6.3) should be one of slow and consistent drawdown until sometime in May, with refill by the end of July.

Grand Coulee operation (Figure 6.4) shows likely drawdown times and levels for the year. Still, from the exceedance probability plot, there is about a 20% chance that there should be no drawdown of Grand Coulee during the season. From the same plot, there is about a 10% chance that Grand Coulee should be drawn down to its lowest allowable level.

Dworshak operation (Figure 6.5) is fairly steady and consistent until March. Thereafter, refill begins, but never achieves it target value of 3,468 KAF, probably due to the relatively low unit value of storing energy in Dworshak and the absence of large flow volumes through Dworshak to justify keeping high hydropower heads.

Flow at The Dalles under HEC-PRM operation (Figure 6.6) is relatively low. Still, these low flows are unlikely to violate the system-wide hydropower penalty applied to flows at The Dalles.

6.7 Data Management for Many HEC-PRM Runs

The estimation of rule curves and monthly probability distributions of storage and flow for each reservoir and estimation of monthly system-wide hydropower production from multiple HEC-PRM runs would require establishment of substantial database capability. This database would be required to capture, store, and manipulate HEC-PRM results to create a variety of graphical and tabular output for particular reservoirs and reaches in the system.

For this limited study, a spreadsheet package was used, with a macro language, to perform the data manipulation and display. HEC-DSSUTL macros were used to export results into a spreadsheet-compatible form.

6.8 Conclusions

HEC-PRM has been applied to a seasonal operation problem for the Columbia River System. The results show the likely behavior of storage and flow under a range of likely inflow conditions for the 1994 January-July operating season. As with simulation model results, additional estimates of system-wide power yield and other measures of performance can be estimated from these flow and storage results. The HEC-PRM results might be able to contribute to seasonal operation planning by suggesting rigorously-derived economic operational strategies for the system and providing a "second opinion" on seasonal operations. The results of this application are consistent with the strategic operating results for a dry year presented in Chapter 3.

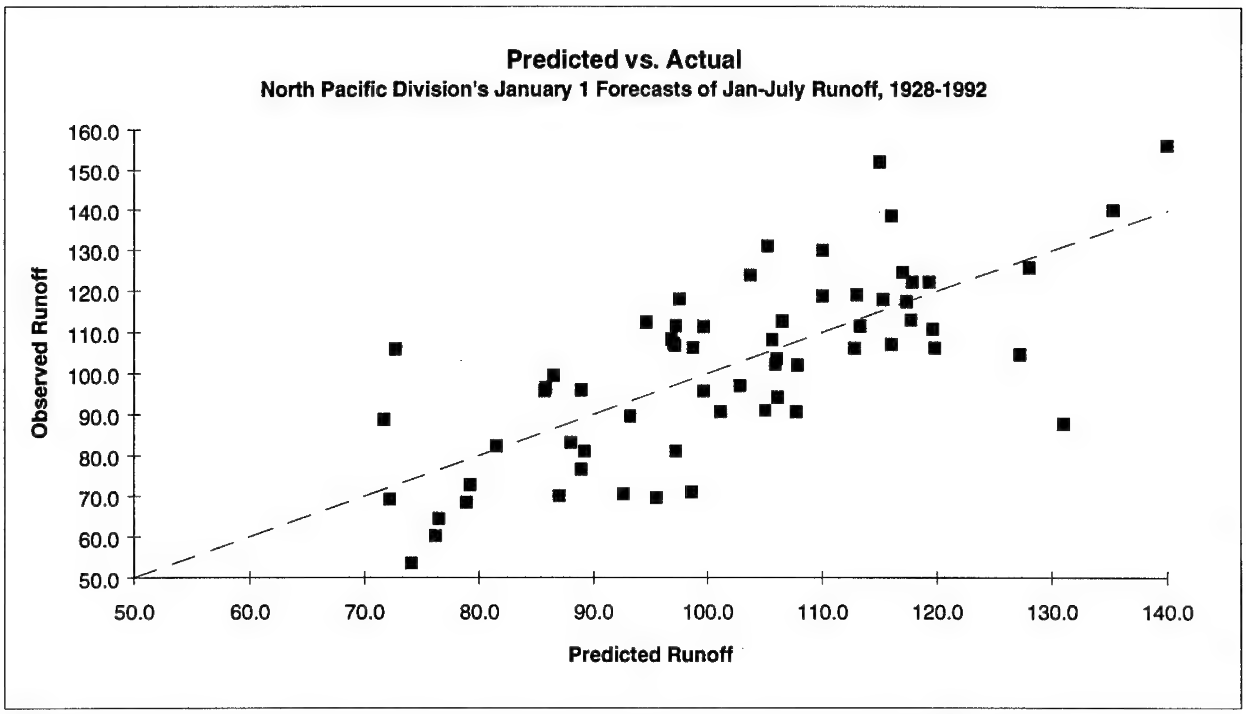
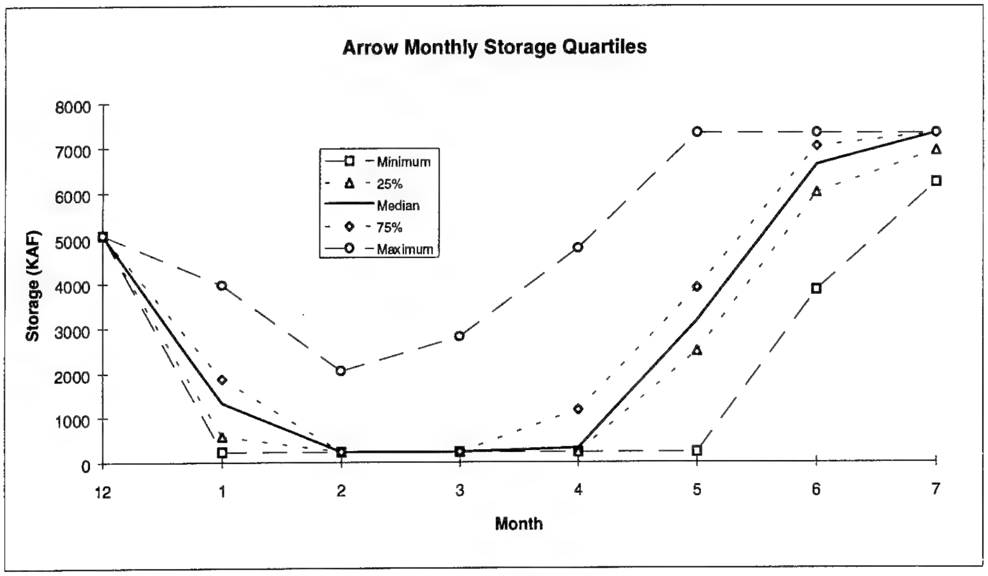
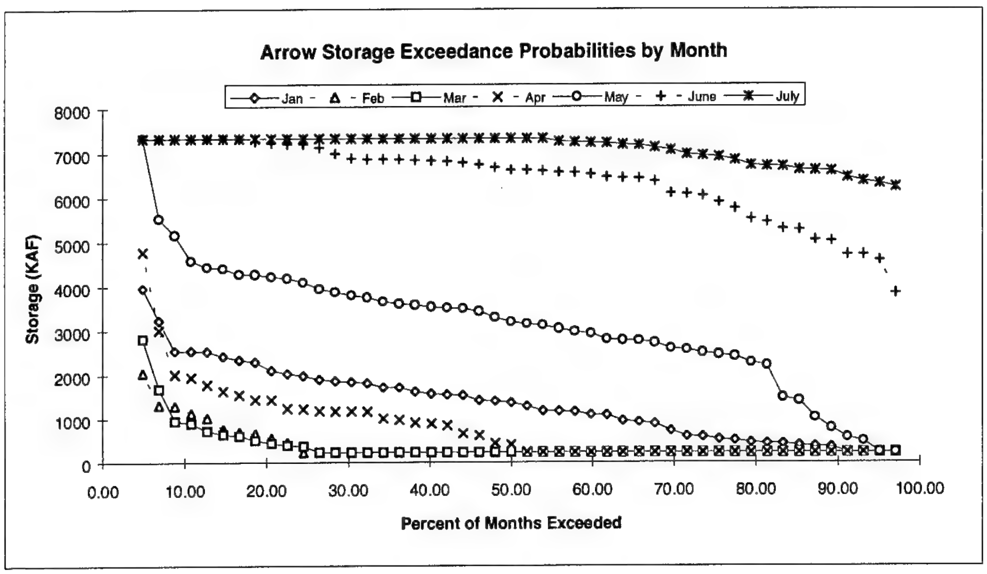


FIGURE 6.1 Runoff Forecasts Predicted vs. Actual, January-July 1928-1992





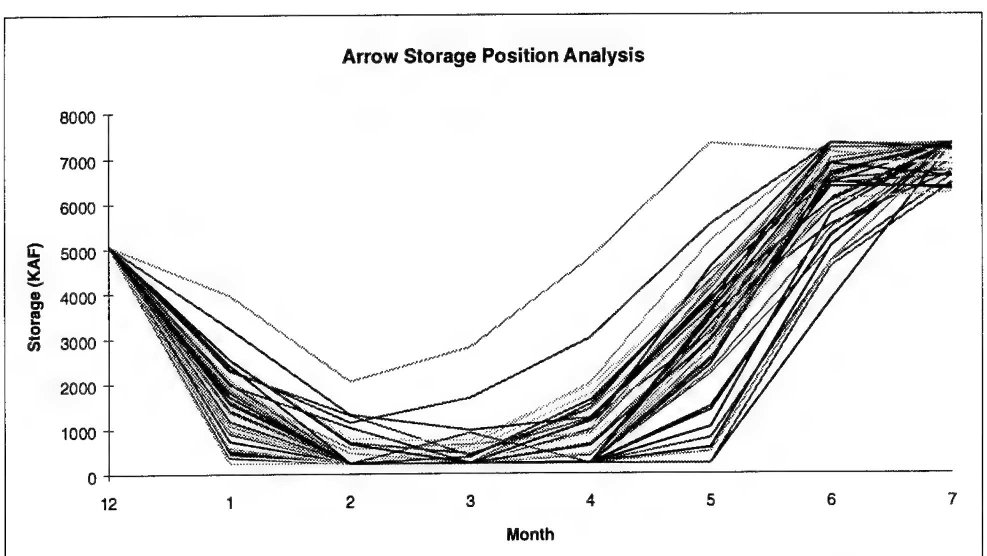
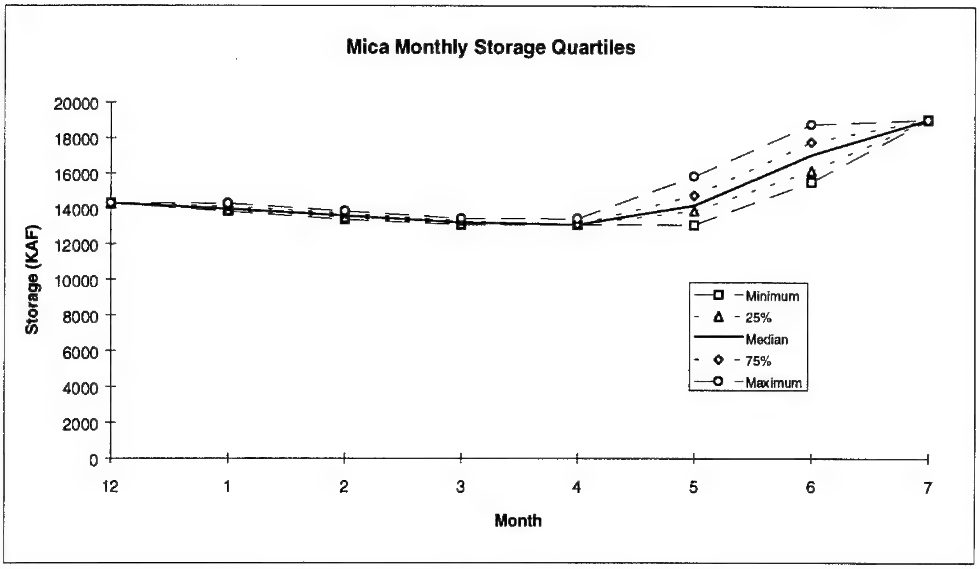
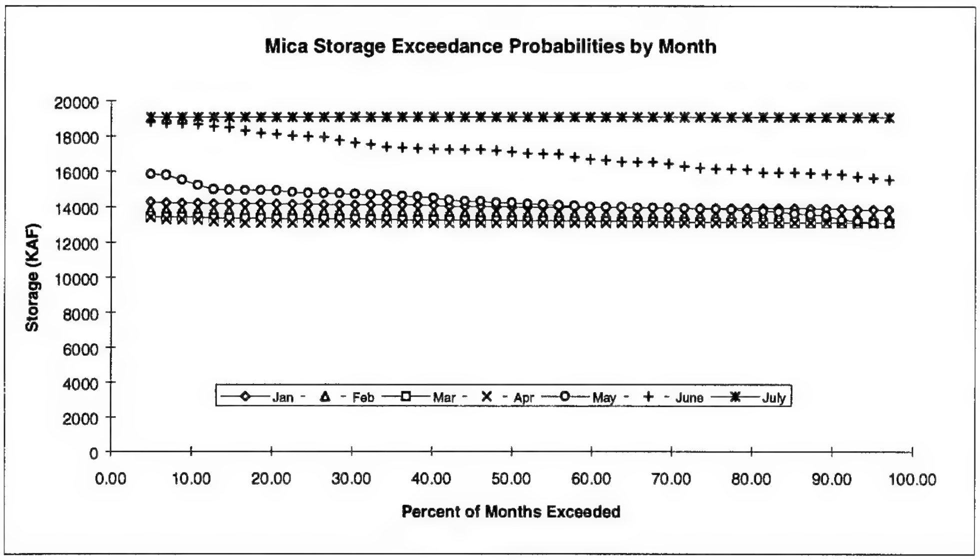


FIGURE 6.2 Annual Operation Storage Results for Arrow





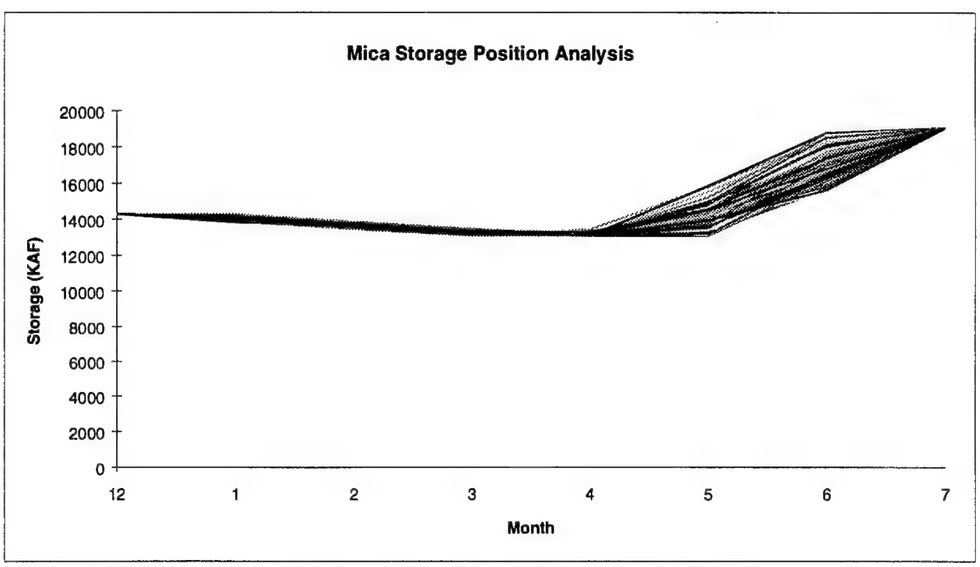


FIGURE 6.3 Annual Operation Storage Results for Mica

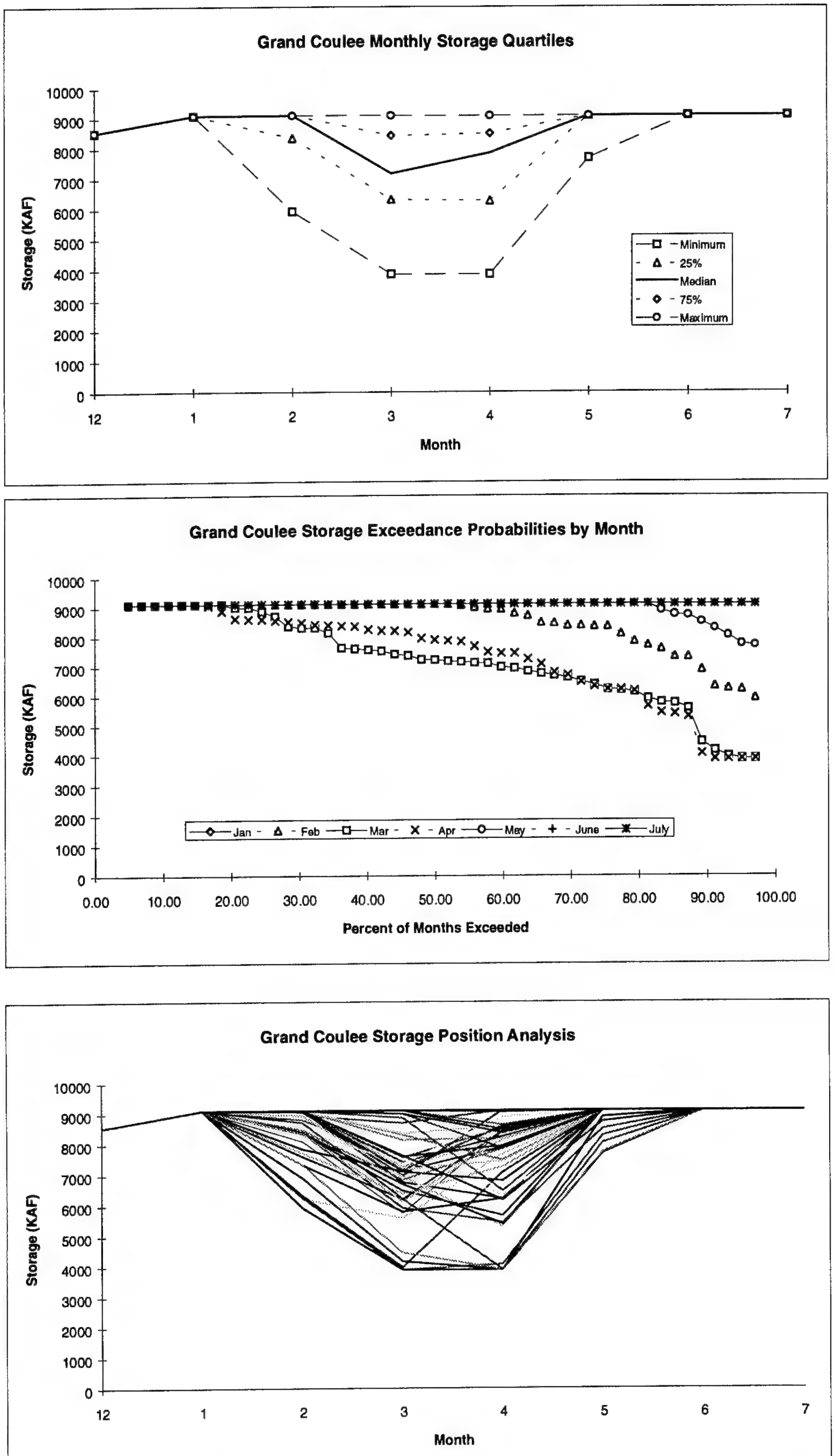
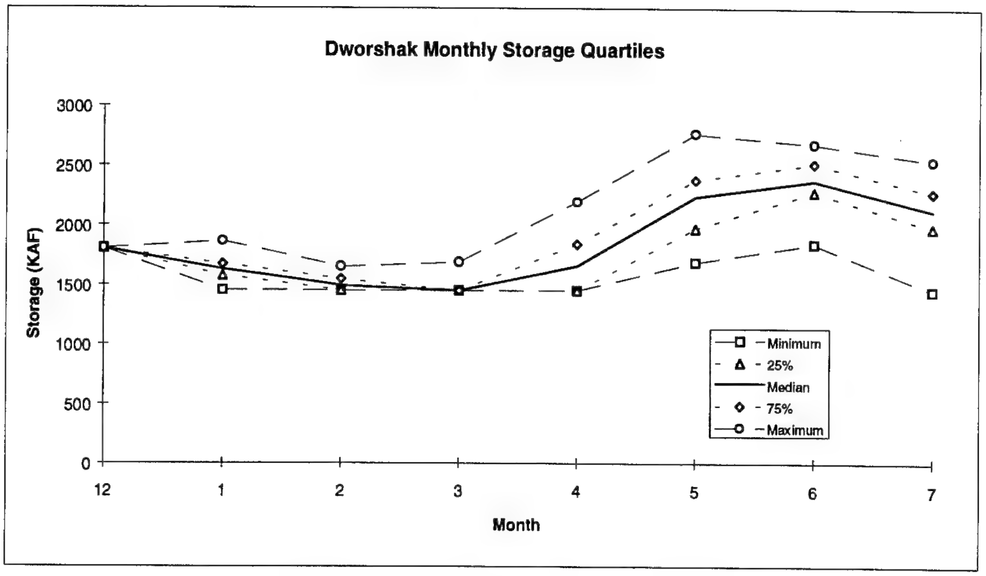
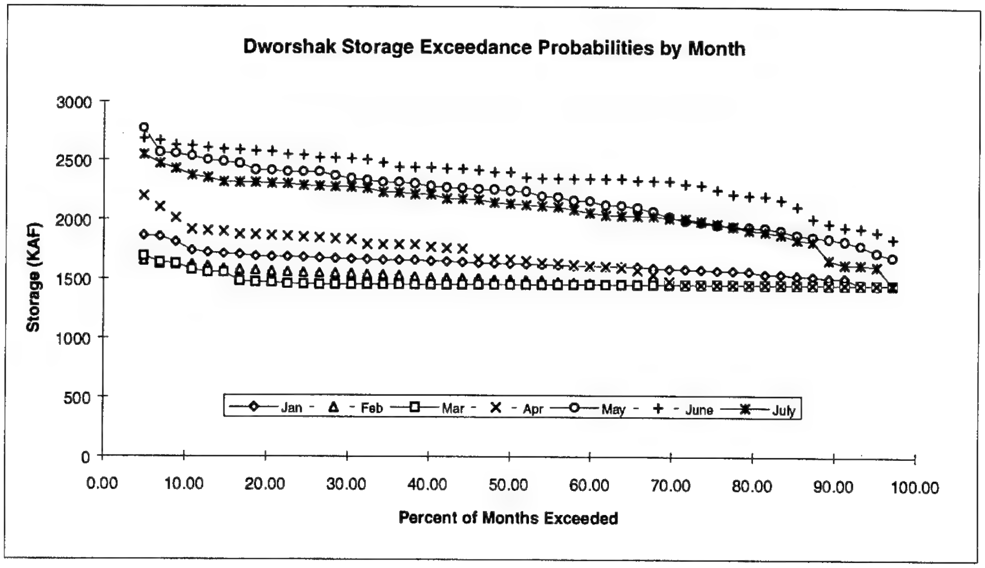


FIGURE 6.4 Annual Operation Storage Results for Grand Coulee





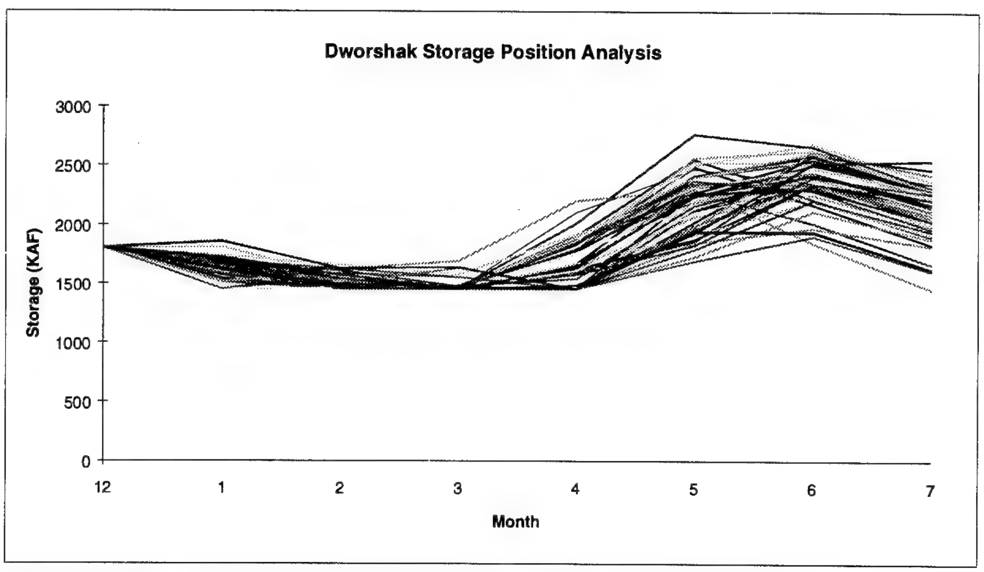


FIGURE 6.5 Annual Operation Storage Results for Dworshak

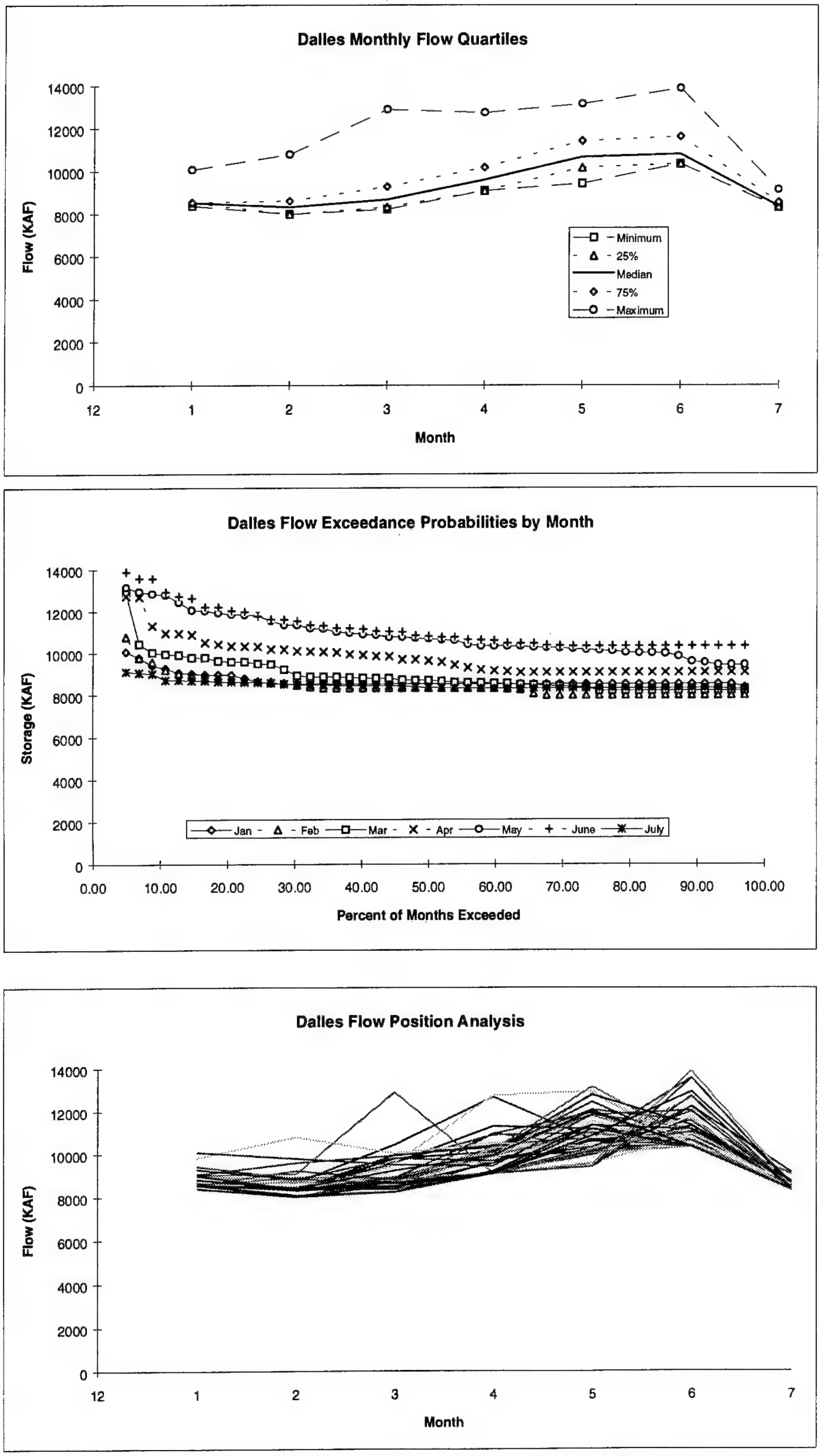


FIGURE 6.6 Annual Operation Flow Results at the Dalles

Chapter 7

Conclusions and Recommendations

7.1 Conclusions

The establishment of viable operating rules are most important in reservoir system management. One intent of HEC-PRM is to suggest reservoir system operations that are optimized explicitly for a quantitative statement of system operating objectives. This study has applied a HEC-PRM model of the Columbia River System to the development of system operating rules. The results of this application of HEC-PRM lead to the following conclusions.

1. HEC-PRM results can be used to suggest modifications in operating rules for the Columbia River System. Operating rules were inferred from HEC-PRM results by various data displays and comparison with current operations represented by HYSSR results.

2. Modifications to current operating rules should be refined, tested, and evaluated using simulation tools. The use of simulation models (such as HYSSR) to refine, test, and evaluate modifications to operating rules compensates for HEC-PRM's foresight in operations, monthly time-step, and sometimes coarse representation of the system and its operating objectives.

3. The overall operation strategy suggested by HEC-PRM is similar to current operations represented by HYSSR results. Annual drawdown and refill of system-wide storage under HEC-PRM is very similar to HYSSR results for the 50-year period examined. HEC-PRM operations differ from those of HYSSR mostly in the allocation of total storage in the basin.

4. The most significant suggestions arising from HEC-PRM results are (1) to draw down Grand Coulee less frequently and (2) to a lesser degree. This operation entails greater and more flexible operation of Arrow and Duncan. Suggestions for modifying other reservoirs in the system are less dramatic.

5. HEC-PRM can be applied to seasonal operation problems on the Columbia River System. There are many potential approaches for applying HEC-PRM to seasonal operational problems. A simple approach was demonstrated to predict promising operational decisions based on historical inflow data updated to reflect current runoff forecast information. This forecast-modified inflow data is routinely prepared by NPD staff in the course of current seasonal operating studies. While the results of these HEC-PRM runs can be employed in ways similar to current simulation (HYSSR) results, the HEC-PRM results are explicitly based on economic concerns. Thus, HEC-PRM may provide a useful "second opinion" on seasonal operating problems.

6. Seasonal operating results for HEC-PRM for the current dry year are consistent with HEC-PRM operations during dry years over the 50-year analysis. This comparison supports the idea that HEC-PRM results are stable in their structure, not varying greatly with small changes in inputs.

7. Optimization modeling may compliment simulation modeling for both strategic and seasonal operation studies. HEC-PRM models are not a substitute for simulation modeling, but represent a different modeling approach which can provide economic justification and promising suggestions for operational and planning decisions.

7.2 Recommendations

The recommendations of this study can be classified into those regarding strategic operating rules, seasonal operations, alternative screening applications, and refinements to the Columbia River System HEC-PRM model.

Strategic Operating Rules

The suggestions made for modifications to current operations based on HEC-PRM results should be refined, tested, and evaluated by simulation modeling. Since the operations are overall similar to current operations represented by HYSSR, it seems appropriate for NPD to perform this refinement and testing using HYSSR.

Seasonal Operations

Additional work on the application of HEC-PRM to the January-July operating period appears warranted. The preliminary application of HEC-PRM presented here for the January-July operating period demonstrated some of the values and limitations of applying HEC-PRM to seasonal operation problems. Additional opportunities for applying HEC-PRM to this and other seasonal operating periods were presented in Chapter 6.

The August-January operating period also might be promising for application of HEC-PRM. The August-January period is typically one of scheduled drawdown for the Columbia River System. Initial storage conditions for this period are known with some precision, as the system's refill period is typically completed by the end of July. The August-December period is also one without major runoff forecasts, making it likely that the historical record would provide directly a representative range of potential system inflows. Also, runoff during this period is steady and predictable relative to the January-July season, making deterministic optimization directly useful for suggesting drawdown schedules for the system based on economic criterion.

The option of incorporating a linear program solver into HEC-PRM should be explored. The highly-efficient network flow solver basis for HEC-PRM requires some simplification of the system and system penalties, particularly for representation of system-wide hydropower demands, multi-reach navigation, multi-period flood control, and multi-reach fish passage problems. However, operational uses of HEC-PRM are far less computationally demanding than

HEC-PRM runs spanning the historical period. This suggests that a slower, but more general linear program solver, which could address the problems identified above, might have significant potential.

Alternative Screening Applications

HEC-PRM can be applied for preliminary examination of planning alternatives for the Columbia River System. Aside from the use of HEC-PRM for development of strategic and seasonal operating rules, HEC-PRM has also been shown to work effectively as a screening model for quickly evaluating alternative system planning options.

Refinements to Columbia River System HEC-PRM Model

Some improvements might be made to the current HEC-PRM Columbia River System model. Suggestions include:

- improvement in seasonal representation of hydropower penalties,
- more explicit representation of Brownlee operations,
- incorporating fish penalties at additional locations, and
- inflow hydrology refinements and extension.

Appendix A

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Appendix B

Methodologies for Developing Operation Rules from HEC-PRM Results

Implicit Stochastic Optimization

The development of reservoir operation plans by abstracting operating rules from extensive deterministic optimization results is sometimes known as "implicit stochastic optimization" (Whitlatch and Bhaskar, 1978; Klemes, 1979; Karamouz, et al., 1992). The approach relies on using a long record of historical or synthetic hydrologic inflows to represent the uncertainty in inflows. The patterns seen in the deterministic optimization results, which have perfect knowledge of future inflows, should therefore represent optimal rules for operations even under uncertainty.

The major advantages of implicit stochastic optimization over explicit stochastic optimization, such as stochastic dynamic programming and stochastic linear programming, is the much greater computational feasibility of deterministic optimization (Young, 1966) and the relative ease of establishing input data sets needed for implementing deterministic optimization. Explicitly stochastic optimization methods, for example, typically require an explicit stochastic model of stream flows, which is usually elusive. There is even some work to suggest that the rules produced by implicit stochastic optimization are superior to those produced by explicit stochastic optimization under some circumstances (Karamouz and Houck, 1987).

Ideally, if a deterministic reservoir optimization is performed with a long enough hydrologic record, a contingency table could be developed to establish the mean optimal release from each reservoir given the current month, current storages, and current inflows throughout the system. This was originally done by Young (1966) for a single idealized reservoir using 5,000 periods of synthetic inflows with one season. It is unlikely that this ideal contingency table approach could be developed for most real reservoir systems that have significant monthly variation, multiple reservoirs, and less than a century of hydrologic record.

Nevertheless, implicit stochastic optimization approaches that have lesser requirements and produce more approximate rules have been common in the reservoir optimization literature (Young, 1966; Jettmar and Young, 1975; Whitlatch and Bhaskar, 1978; Bhaskar and Whitlatch, 1980; Trott, 1979; Karamouz and Houck, 1982; Karamouz, et al., 1992). Most applications of implicit stochastic optimization have been to cases with only a short stream flow record, typically less than 40 years. In these cases, use of the historic record would provide a very limited and perhaps unrepresentative example of the range of stream flow experiences which are possible in the future. In these cases, synthetic stream flow generation has been employed to provide the statistical equivalent of a long stream flow record (Karamouz, et al., 1992). While synthetic stream flow generation may be unavoidable in the absence of a long stream flow record, there are

important methodological difficulties with this approach (Klemes, 1974). Still, some have found that the use of even rather short (64-year) historic records can yield operating rules essentially the same as those found using longer synthetic stream flow records (Jettmar and Young, 1975).

Deterministic Optimization for "Typical" Years

Another common approach for developing optimization rules from deterministic optimization results is to specify a hydrology and water demands for a "typical" year or a set of typical years. Deterministic optimization is then used to find optimal operations for such years and these optimal results are then interpreted to find operating rules, often with the aid of simulation (King and Evenson, 1972). Rules developed by this approach may be informative, but will not be applicable to as wide a range of conditions as those developed by implicit stochastic optimization, using a much longer stream flow record.

B.1 Rules from Results

A variety of general approaches are available for discerning reservoir operation rules from optimization results. Variants of these approaches have been employed in previous optimization studies.

Each of these approaches seeks to detect and substantiate a pattern in historical optimal operations that can be reduced to "rules" which are based on the reservoir operator's current state of knowledge. Thus, operation rules must be based on known states such as: the current month, current storage, and current or forecast inflows. For the Missouri River system (USACE, 1994b), some typical examples of operation rules would be:

- A storage rule based solely on the month,
  "In February, keep Fort Randall storage at 3.5 MAF."
- A storage rule based on the current month and system storage,
  "In July, if total storage > 64 MAF, keep 22 MAF in Oahe."
- A release rule based on system storage,
  "In July, for total storage between 50.5 and 59.0 MAF maintain a flow of 25,000 cfs + 706*(Storage - 50.5 MAF) at Sioux City."

The major difficulty in detecting these rule patterns in long-term optimization results is the amount of optimization result data available. For the case of the 90-year record used in the Missouri River exercise, a total of 13,248 optimal release and storage decisions were provided, in addition to input inflow data and data on consequent downstream flow consequences of release decisions. The four general approaches discussed below are employed to identify consistent trends in large amounts of data.

Intuitive Approaches

Intuitive approaches to discerning reservoir operation rules employ our innate and educated abilities as engineers to detect significant patterns in data. We all feel that we are able to "see" when plotted data seem to fit a linear trend.

The use of intuition in identifying and substantiating apparent "rules" in optimization results is greatly aided by the use of graphical and statistical tools. Descriptive statistics, histograms, scattergrams (data plots), and other techniques all present data in a form conducive to our "seeing" trends. Statistical and data analysis software packages can be very valuable in quickly providing a wide variety of such displays and descriptive statistics to the rule-maker. As described in the main body of this report, an educated intuition was the major approach used in developing the rules suggested in this report.

The utility of intuition in rule-making is limited by the intuitive abilities of the rule-maker and the complexity of the rule-making task. There may always exist a more perfect pattern that is too complex for a rule-maker to "see." Also, different rule-makers might "see" different patterns. Finally, the complexity and quantity of the data may be difficult to present in a form conducive to intuitive rule-making. The limitations of intuition for rule-making are those of the individual, human rule-maker.

Regression Approaches

Regression typically tries to develop equations which predict optimal decisions, such as releases, based on input data, such as current month, current storage, and forecast inflows. Regression techniques typically assume linear relationships between these variables and attempt to best "fit" the regression equation by finding parameters for the equations that satisfy some "fit" criterion, such as minimization of the sum of squared deviations between the optimal decisions and decisions predicted by the linear regression model.

Regression was first employed for developing reservoir operation rules from optimization results by Young (1966) and has been employed by others since (Jettmar and Young, 1975; Bhaskar and Whitlatch, 1980; Karamouz and Houck, 1982; Karamouz, et al., 1992). Before using regression to estimate an operating rule, specific dependent and independent variables must be defined. Independent variables would include those things known at the time of real operations, such as the current month, current storage, and current inflows. The dependent variable in the regression would be some operating decision which must be made, such as a release rate or a storage target. Given the relative ease of performing regression analysis with contemporary statistical packages, it is easy to explore a variety of dependent variables and several combinations of independent variables. The specification of independent and dependent variables is rather subjective, aided by intuition and judgement, reservoir operation theory, simulation results, and previous regression results.

Most use of regression for developing reservoir operation plans has been for single reservoirs (Young, 1966) or small multiple reservoir systems with a single operating purpose (Bhaskar and Whitlatch, 1980; Karamouz, et al., 1992). In application of HEC-PRM to the

Missouri River system, regression approaches were tried extensively, but were found to be almost entirely inadequate (USACE, 1992). For larger reservoir systems, such as the Missouri River system, there are many possible sets of independent and dependent variables. The operation of multi-purpose reservoir systems, where the optimal operation is driven both by storage, release, and downstream flow values is also less likely to be revealed by simple linear relationships. In addition to the engineering judgement, intuition, theory and other aides to specifying independent variables, step-wise multiple regression can be of use in determining which of many possible independent variables tend to best explain variation in a particular release rate or storage level.

Reservoir Operation Theory

Reservoir operation theory can be of great use in suggesting the form of operating rules that might be inferred from optimal operation results. Work on optimal rule forms and patterns can be particularly useful (Clark, 1956; Mass et al., 1966; Kelman, et al., 1989; Loucks and Salewicz, 1989; Johnson, et al., 1991). Some common examples of these optimal operating rule forms are:

- Space rules (Clark, 1956; Maass et al., 1966; Johnson, et al., 1991), which seeks to balance storage between reservoirs in parallel to minimize the likelihood of spills,

- Pack rules (Maass et al., 1966), which maintain storage at high levels as long as possible to increase hydropower heads and production, and

- Hedge Rules (Maass et al., 1966), which reduce reservoir releases early in a drought to reduce the risk of shorting more critical release uses later in a drought.

Other rules are suggested by work by other authors and the practice of reservoir operators. However, many of these additional rule forms have not been formally stated or examined.

B.2 Mixed Simulation-Optimization Approaches

Simulation-optimization approaches to developing operation rules for reservoirs employ optimization models to suggest initial operating rules and simulation models to test and refine these rules. This process may involve several cycles of optimization and simulation runs, often conducted in a fairly adaptable and flexible, but systematic way. Almost every practical rule-making exercise undertaken using optimization has conjunctively employed simulation modeling (for example: Jacoby and Loucks, 1972; Evenson and Moseley, 1970; King and Evenson, 1972; Toebes and Rukvichai, 1978; Bhaskar and Whitlatch, 1980; Karamouz, et al., 1992). The simulation modeling of the Missouri River system demonstrated the value of simulation studies for testing and refining rules inferred from HEC-PRM results (USACE, 1994b). Some of the general rationale and uses for simulation are presented in Table B.1 and discussed below.

Table B.1
Rationale and Uses for Simulation Modeling in Optimization Rule-Making

Rationale

Simulation models typically represent the system better than optimization models.

Simulation models perform some "what if" studies more easily than optimization models.

Simulation models typically run faster than optimization models.

Simulation modeling is typically better understood and accepted than optimization modeling.

Uses of Simulation

Refinement of suggested optimization-based rules to increase realism in system operation.

Testing of suggested optimization-based rules for:

- feasibility
- detailed operational implications
- comparison with existing operation plans
- evaluation of desirability using more detailed operational performance measures

Rationale for Use of Simulation

There are several reasons to employ simulation in conjunction with optimization for reservoir rule-making. First, optimization models must typically be somewhat simpler than simulation models of a reservoir system. Optimization models typically require that definitions of the system and its objectives conform to specific mathematical conditions needed to implement a solution method. For HEC-PRM, an example is the requirement that all penalty functions be convex. Simulation models suffer much less from such constraints. This makes it possible to test rules developed from optimization results with more realistic simulation models. The greater realism of simulation models also provides opportunities to refine operation rules suggested by optimization results to make them more appropriate for the real reservoir system.

A second reason for employing simulation models in rule-making with optimization is the often greater ability of simulation modeling to perform "what if" studies. Specific flood control or drought scenarios can be studied easily using proposed operation rules in a simulation model. This would be awkward and often inappropriate for optimization models.

A third reason for employing simulation models is the greater speed of most simulation models. A larger number of specific cases can be studied by simulation modeling than would be possible by optimization. However, optimization results might suggest some of the more fruitful scenarios to be tested.

The final, and perhaps most important reason to employ simulation models is the greater acceptance enjoyed by simulation modeling and the frequent relative ease of explaining simulation results. Even where operating rules are unchanged by simulation modeling, simulation modeling is probably necessary to render the rules understandable and acceptable to concerned technicians and individuals.

Uses for Simulation

Rule Refinement

Since simulation models can both represent the reservoir system in greater detail and be executed more quickly than optimization models, simulation models are useful for refining the details of operation plans suggested by optimization results. As such, the optimization-based suggested rules may serve mainly as a point of departure for more traditional simulation studies of operation plans (USACE, 1994b).

Simulation modeling can also be used to refine the optimization model (Karamouz, et al., 1992). In this case, a cycle of optimization, rule-making, and simulation model proceeds iteratively until a satisfactory set of rules is developed.

Rule Testing

Again, since simulation models can represent the system in more detail and have already gained some acceptance, in most cases, simulation modeling is a rather inexpensive and effective approach to testing operation plans developed from optimization results. Such simulation tests have a number of objectives:

Do the suggested rules closely match the storage and release behavior from the optimization model? By implementing the suggested rules in a simulation model, rule-based storages and releases can be compared with those obtained directly from the optimization model (Bhaskar and Whitlatch, 1980; USACE, 1994b). This comparison can be used to see if the suggested operation rules well represent the optimization results.

Are the suggested rules feasible? Unless the suggested rules are thoroughly thought out, it can be possible for rules to suggest impossible behavior. For instance a release rule based solely on the month can suggest release volumes in excess of available storage and inflows.

Are the suggested rules really optimal? Since a simulation model can usually represent the reservoir system in greater detail than an optimization model, implementing the suggested operation rules in a simulation model and performing sensitivity analysis on the parameters in the suggested rules can conceivably improve the optimality of the suggested rules. A similar test is

to compare the detailed performance measurements from a simulation model employing existing operation plans with those from a simulation employing the suggested operation plan. If the optimization model represents too great a simplification of the real system, existing operations might in fact be superior to those suggested by the optimization model.

Do the suggested rules perform well under extreme detailed scenarios? It is often desirable to test a proposed operation plan under detailed flood control, drought, or emergency operation circumstances. If the suggested operations are not suitable for such emergency operations, the suggested operations, the importance of the chosen scenarios, and other responses to the proposed scenarios might be further examined.

Often, further optimization and simulation studies would be useful for such questions. For instance, the introduction of further constraints to the optimization to facilitate emergency operation can give cost estimates of preparedness for such emergencies. In some cases, there might be less expensive approaches for emergency preparedness.

Implementation Issues

The use of simulation in conjunction with optimization is greatly facilitated by the prevalence of existing simulation models for reservoir planning and operation studies. Almost all large reservoir systems have one or more existing simulation models. Still, most existing reservoir simulation models are likely to require considerable modifications to accept the diverse forms of operating rules that are likely to be developed from deterministic optimization (HEC-PRM) results.

In many cases, the most difficult aspect of simulation studies of this nature is the incorporation of more explicit economic or environmental performance indices in an existing simulation model. While this may be a burdensome and time-consuming task, the presence of economic and environmental performance indices in a model can be of long-standing utility well after an operation plan study is completed.

B.3 Some Potential Pitfalls

There are several potential pitfalls in the development of operation plans from optimization results. Most of these can be detected by the use of simulation studies to test and refine suggested operation plans. Some of these pitfalls are probably mostly of academic importance, but may have practical importance in specific cases.

Infeasible Operations

It is possible for the set of rules suggested by optimization results to result in infeasible operations. Infeasible operations are those that would not be allowed by the constraints in the original optimization model or not physically possible in the real reservoir system. The likelihood of infeasible operations increases when the reservoir system faces more severe drought or flood events than those present in the hydrology entered in to the optimization model.

Infeasible operations are also more likely to result from suggested rules which do not closely mimic the optimized operation of the reservoir system. An example of an infeasible operation is a release rule which specifies releases greater than the sum of the available storage and inflow.

Technical Suboptimality from Failure to Represent Uncertainty

The results of the deterministic optimization model represent an ideal operating policy, with perfect forecasting of future inflows and the perfect predictions of the value of different reservoir purposes. As such, it is unlikely that any set of rules triggered by current operator knowledge (such as current month, storage, and inflows) will be able to perfectly mimic the optimized results. This implies that the suggested rules will not produce as good an operation as that given directly by the optimization results.

The divergence between the rules suggested by the optimization results and the optimization results represents, in some sense, the cost of uncertainty in streamflow forecasts. It may be possible for a more rigorous stochastic optimization to provide rules with less divergence. However, such stochastic optimization is rather difficult or impossible for many real reservoir operation problems.

Technical Suboptimality from Optimization Model Simplification

As mentioned before, most optimization models require some simplification of the real reservoir operation problem. For HEC-PRM the need for the objective function to be convex is such a simplification. This implies that the optimal operations suggested by the optimization model may not be the real optimal operation. While some of this phenomena may be tested by simulation modeling, the exact optimal operation for the real system is in practice usually unknowable.

Oversimplification of Rule Forms

There is a great temptation to seek a few simple rule forms when developing operation plans from optimization results. This principle of parsimony is generally very useful and well accepted in professional and scientific fields. However, it may be possible for more complex rule forms to more closely mimic the optimization results and improve reservoir operations.

Overly Complex Rule Forms

Rule forms that are overly complex might more closely mimic the results of the optimization model. However, too complex a set of operating rules can result in a degree of spurious correlation between rule-based operation and optimization results. Complex operating rules also make simulation studies more difficult.

Replication of Existing Operation Through Rule Form Selection

If current operation plans are used as a guide for developing new operation plans from optimization results, it is likely that the "new" operation plans will be very similar to the existing operation plan. The use of the same form for new operating rules as existing rules will often result in a close replication of existing policies. Some attempt should always be made to see if rule forms different than existing forms can closely mimic optimization results. Despite such efforts, in many cases it is likely that "optimal" operating plans will be rather close to existing operating plans.

B.4 Conclusions

The development of operation plans from deterministic optimization results using long hydrologic records has advantages over traditional approaches employing simulation and engineering judgement or stochastic optimization. This approach to operation plan development has a long history in the engineering literature with a large number of plan development approaches being suggested.

In general, a combination of a variety of plan development approaches is likely to be preferred. In particular, the use of simulation modeling in conjunction with optimization results is almost essential to the technical and practical success of any rule-making exercise based on optimization results.

Appendix C

Detailed Suggestions for Further Applications of HEC-PRM

Application of HEC-PRM to the Columbia River System has been demonstrated for comparison of planning alternatives (USACE, 1993) and preliminary operating rule development (this report). These studies suggest several areas of potential improvement for the HEC-PRM model of the Columbia River System.

C.1 Uses for HEC-PRM Results

Several uses for the HEC-PRM model and its results for the Columbia River system are presented below. Most of these could be done by the North Pacific Division, though some assistance from HEC might be useful or desirable.

HYSSR Simulation of Operating Rule Suggestions

Operating rule suggestions inferred from HEC-PRM results require substantial refinement and testing by simulation models before they can be applied. Since the "optimized" operations are structurally similar to current HYSSR operations, HYSSR seems the best model for simulation testing.

Examination of the July-to-January Drawdown Period

Use of HEC-PRM to examine operations during the July-to-January drawdown season appears to be particularly promising. This period is characterized by probably the most regular and predictable inflow rates to the system and falls between the period of greatest system refill and the availability of forecasts for operations during the January-to-July operating season. Operation during the July-to-January season is typically based on less variable system operating rules than during the January-to-July period. These conditions seem conducive for application of HEC-PRM.

A July-to-January application of HEC-PRM would consist of many July-to-January season (6-month) runs, one analysis period for each year of hydrology available. Each 6-month analysis period would begin with storage levels at the end-of-July refill level. Each analysis period would end with either a fixed target storage level for each reservoir, or with a storage level penalized based on deviation from a target storage level (as was done in the Chapter 5 example).

These results should be similar to those described for the July-to-January period in Chapter 3. However, by varying the initial storage levels to reflect refill conditions in a current year, the results could be tailored to conditions in each year. Such HEC-PRM runs should not be difficult to implement and interpret.

Additional January-to-July Period Studies

Preliminary application of HEC-PRM to January to July operations appears promising. NPD might wish to investigate further the potential use of HEC-PRM in seasonal refill studies.

Additional Alternative Screening Studies

The Phase II report of HEC-PRM applications of HEC-PRM to the Columbia River System discussed the use of HEC-PRM to examine preliminarily and evaluate different strategic alternatives for system operations (USACE, 1993). That report compared three alternative operation scenarios, current operating purposes and conditions, operations without consideration of hydropower benefits, and current operating purposes with additional storage capacity available at Mica. Additional alternative scenarios might be similarly examined using HEC-PRM.

C.2 Small Improvements in the Existing HEC-PRM Model

Penalty Function Improvements

There will always be room for improvement in the set of penalty functions available for a system. This applies also to the HEC-PRM model of the Columbia River System. In particular, there remain a number of locations in the system where fish penalties might be desirable, such as at Priest Rapids, below Libby, below Columbia Falls, and in Hungry Horse reservoir. Some additional recreation penalties might also be added, though we feel that these would have little impact on the overall program results. Some refinement of hydropower penalties might be desirable to reflect seasonal changes in the value of hydropower production. Current hydropower penalty functions seem to be standardized on the maximum hydropower benefit for each season. Standardizing hydropower penalties based on the annual maximum hydropower benefit for each project may introduce more realistic seasonal variations in hydropower values.

Brownlee Operations and Penalties

For the analyses presented in this report, Brownlee operation was represented by HYSSR results from the Phase II HEC-PRM Columbia River System application, as discussed in Chapter 2 and Appendix D. This representation of Brownlee is not entirely satisfactory since it allows no coordinated operation of Brownlee with other reservoirs. To represent Brownlee explicitly in the HEC-PRM model would require development of appropriate hydropower and other penalties for Brownlee, reflecting its different hydropower market.

C.3 Major Improvements in the HEC-PRM Model for Columbia River Applications

Two major improvements are suggested for the HEC-PRM model for application to the Columbia River System, as well as other river basins. These are: 1. incorporation of an option for a linear program problem solver for improving representation of system-wide hydropower, flood control, and multi-reach navigation and fish objectives, and 2. development of a graphic user interface to facilitate HEC-PRM problem formulation and results interpretation. The linear program solver modification is discussed under headings indicating how a linear program solver would improve representation of different project purposes.

Adding a Linear Program Solver to HEC-PRM for System-wide Hydropower

A major shortcoming of the current Columbia River HEC-PRM application stems from assessing hydropower penalties directly based on hydropower energy output from individual projects. Since the Columbia River basin electric grid is largely base-loaded by hydropower and hydropower provides essentially all peak power supplies, hydropower penalties might be more realistically assessed on a system-wide basis.

Assessing hydropower penalties on a system-wide basis would entail estimating hydropower energy generation at each project, summing this generation for each time-step over the entire system, and then placing a piece-wise energy penalty on this system-wide hydropower production. This is in fact done, essentially, in some of Quentin Martin's formulations of this problem (Martin 1983, 1987).

The current HEC-PRM model cannot assess hydropower penalties system-wide because it is based on a network flow programming (NFP) solver. System-wide hydropower penalties require additional linear constraints that span the system for each time-step. These additional constraints do not fit nicely into a NFP formulation. However, the additional constraints are all linear, and so could be handled by a linear program (LP) solver. Quentin Martin, the developer of the current hydropower solver, uses an LP solver in some of his work (Martin, 1987).

There are some disadvantages to incorporating system-wide hydropower penalties in to HEC-PRM:

1. It will require some re-programming to formulate the additional system-wide hydropower generation constraints.

2. It will require additional re-programming to allow an LP solver option and selection of LP solver code.

3. The LP solver will be much slower than the current NFP solver. This should not be a problem for HEC-PRM runs with short hydrologic periods, as would be the case for most annual or seasonal operation planning applications. Such run-times might be prohibitive for period-of-record type runs, especially for large systems.

The advantages of adding an LP solver and system-wide hydropower penalties also might be considerable, and include:

1. It will allow more realistic representation of hydropower operations in HEC-PRM models.

2. It would facilitate development of project and system-wide hydropower penalties, since project hydropower penalties would be based solely on physical energy generation characteristics which should be well-known and the system-wide economic penalties would be based on system-wide energy sales, also well-known.

3. It would facilitate the use of HEC-PRM for annual and seasonal operation planning and perhaps nearer-real-time operations.

4. It should require little change in the current HEC-PRM hydropower algorithm.

Multi-Reach Navigation and Fish Passage with a Linear Programming Solver

A potential shortcoming of the present HEC-PRM model is its difficulty representing penalties for multi-reach navigation and fish passage. For both navigation and fish passage to be effective, barges and fish must often traverse several different reaches. In the present HEC-PRM, penalties for fish and navigation are assessed arc-by-arc. Thus, if barge traffic must traverse 3 reaches, and flows in two reaches are too low, the navigation penalty is twice that of when only one reach has low flow. This is unrealistic. If one reach's flow is too low to permit passage, low flows in additional reaches are of no additional consequence. A similar problem exists for the case of fish passage and migration. Like system-wide hydropower penalties, such multi-reach phenomena do not seem to be easily represented by network flow problem formulations. Linear programming formulations would allow much more explicit model representation of these phenomena. This note presents such a linear programming formulation.

Consider a system of reaches, inflows and withdrawals, with reservoirs and other system elements upstream and downstream:

```
             |             |              |             |
<------O<--------O<---------O<--------O<------.
  Q4    |     Q3      |      Q2      |      Q1     |
```

Several linear constraints can be added to the mathematical program's constraint set to define the minimum flow through the set of reaches Q1, Q2, Q3, and Q4,

$$M <= a1\ Q1 - b1,$$
$$M <= a2\ Q2 - b2,$$
$$M <= a3\ Q3 - b3,$$
$$M <= a4\ Q4 - b4,$$

where M is the minimum flow, or some minimum flow index, for the entire reach sub-system, the Qs are the modeled flows in each reach, and the [a] and [b] parameters can be used to represent the differing geometries or other environmental characteristics of each reach. If all [a] parameters are set equal to one and all [b] parameters are set to zero, M becomes the minimum flow in the system of reaches.

Navigation and fish passage penalties for the sub-system of reaches would then be made functions (hopefully convex) of this minimum flow or minimum flow index, M. The incorporation and solution of this problem in HEC-PRM requires only the ability of HEC-PRM to use a linear program solver.

Improved Flood Damage Representation Using Linear Programming

The current network flow solver for HEC-PRM can have some difficulties representing flood damage penalties. In a network flow formulation, flood damage penalty functions are present for all time-steps. The flooding of a reach for two consecutive time steps imposes twice the penalty of flooding for one time-step. This is likely to greatly overestimate flood damage, since once a structure is flooded, the damage is substantially done for a number of time steps thereafter.

Within network flow programming there are a couple of approaches to resolving this problem. The first is to impose flood damage penalties during only one month of the year, preferably the worst month for flooding. If annual flood peaks almost always occur during a single month, this approach should work well. The second approach is to solve the problem conventionally, with flood damage penalties in each month. If there were any cases where double counting of actual damages occurred, a second solution would be made with the problem modified to eliminate the redundant flood damage penalties. Several of these second-stage runs might be needed to ensure that the flood damage penalty is assessed during the worst month. This second approach could be rather tedious for complex systems with flood control operations occurring at many points throughout a system during a multi-time step flood season.

Adoption of a linear program solver option facilitates more flexible representation of flood damages. Given flows in a reach over several time steps, Q1, Q2, Q3, ... Qn, a peak seasonal flow Qp is specified using a set of linear constraints: Qp >= Q1, Qp >= Q2, ..., Qp >=Qn. The flood damage penalty for the reach is then assessed based on Qp.

Graphical User Interface

The current user interface for HEC-PRM is effective and full-featured, but rather cumbersome for many potential users. The development of a more user-friendly graphical user interface could greatly reduce the resources required for learning use of HEC-PRM and developing and using HEC-PRM system models. Such a user interface should be compatible with other data-management, reservoir operating and data display/data analysis software likely to be in future use by the Corps.

C.4 Conclusions

Some of the suggestions for further application of HEC-PRM for the Columbia River System require little resources, some are mere refinements on existing HEC-PRM applications to this system, and others require major changes in the solution method and programming of the HEC-PRM model. As such, the intent of this appendix was to provide a wide range of options for the employment of HEC-PRM to the Columbia River System.

Appendix D

Penalty Function Changes from Phase II

This appendix presents the details of the changes made to penalty functions since the Phase II HEC-PRM model of the Columbia River System. The Phase II model is described by USACE (1993). These changes are summarized in Chapter 3 of the present report.

D.1 Canadian Project Penalty Functions

Mica Hydropower Penalties

Hydropower penalties were added for Mica and Revelstoke Reservoirs. These were combined for representation at the Mica node in the HEC-PRM model. Revelstoke is largely a run-of-river hydropower operation, particularly when examined at a monthly time-step. The economic data for these reservoirs obtained from NPD were combined and modified into a penalty function format at HEC. These penalties were derived for four seasons. These penalties appear in Table D.1 and D.2 and are plotted in Figures D.1 through D.4.

In deriving the penalty functions for Mica and Revelstoke, penalties were derived from hydropower benefits by subtracting the value of hydropower production for each flow-storage combination from the maximum hydropower value for that season. This appears to be how hydropower penalty functions were derived for the Phase II model.

Upon reflection, this approach to deriving penalties from hydropower benefits seems to excessively damp seasonal variation in hydropower values. For the Mica and Revelstoke data, the variation in the maximum seasonal hydropower value is almost 13%, with winter hydropower production being most highly valued. Creating hydropower penalties by subtracting hydropower values for each release-storage combination from the annual maximum hydropower value would seem to preserve this seasonal variation in hydropower value better.

Libby Recreation Penalties

Penalty functions for recreation on the Canadian portion of Libby reservoir were added to Phase II penalties for Libby storage. These revised Libby storage penalties appear in Table D.3 and Figures D.5 through D.11. Fortunately, the addition of these Canadian recreation penalties made the new composite penalty function for Libby storage converge more closely with the edited (convex) penalty function used in the Phase II model.

D.2 Spalding Fish and Recreation Penalties

A penalty representing loss of recreational fishing at the Spalding control point was added to the flood control flow penalty existing there. The additional fishing penalty, the new composite penalty, and the revised edited penalty function for Spalding appears in Table D.4. A depiction of these revised penalties appears in Figure D.12.

D.3 System-Wide Hydropower Penalty at the Dalles

A monthly-varying system-wide hydropower penalty was added to flow below the Dalles to represent the penalty for failing to meet system-wide hydropower demands. The penalty was taken to begin at some minimum flow, which varied monthly, and had a slope derived to approximate the cost of replacement energy under peak conditions. The minimum zero-penalty flow was taken as the average flow derived from HYSSR results during the four-year critical period. A table of these minimum flows appears in Table D.5.

The slope of the penalty function was estimated using the assumption of a composite Columbia System reservoir, having an elevation of 1,220 ft., and assuming a cost of replacement power of 7.5 cents/kwh. A slope of $78.5/acre-ft was derived for this penalty function.

Table D.1
Mica Hydropower Penalities Part 1

Combined Mica and Revelstoke Hydropower Penalties in Thousands of Dollars												
Storage Status		Normal Full	3/4 Full by elev.	1/2 Full by elev.	1/4 Full by elev.	Minimum Pool		Normal Full	3/4 Full by elev.	1/2 Full by elev.	1/4 Full by elev.	Minimum Pool
Elev. (ft)		2,475	2,423	2,398	2,372	2,320		2,475	2,423	2,398	2,372	2,320
Stor. (KAF)		20,076	14,936	12,869	11,022	8,022		20,076	14,936	12,869	11,022	8,022
Release		Months January, February, and December					Release	Months March and November				
(CFS)	(KAF/mo.)						(KAF/mo.)					
0	0	63,894	63,999	64,897	65,775	67,505	0	64,959	65,055	65,880	66,686	68,275
5,000	302	58,257	58,847	59,885	60,888	62,883	302	59,228	59,797	60,763	61,698	63,557
10,000	604	52,684	53,758	54,928	56,064	58,325	604	53,562	54,603	55,703	56,773	58,904
15,000	906	47,105	48,514	49,817	51,089	53,625	906	47,890	49,266	50,502	51,710	54,121
20,000	1,207	41,543	43,287	44,724	46,132	48,943	1,207	42,236	43,946	45,319	46,665	49,355
25,000	1,509	35,999	38,077	39,648	41,192	44,278	1,509	36,599	38,644	40,153	41,637	44,607
30,000	1,811	30,472	32,885	34,590	36,270	39,630	1,811	30,980	33,359	35,005	36,628	39,877
35,000	2,113	24,935	27,657	29,496	31,312	34,948	2,113	25,351	28,040	29,823	31,584	35,114
40,000	2,415	19,718	22,437	24,412	26,364	30,276	2,415	20,047	22,731	24,651	26,550	30,361
45,000	2,717	14,701	17,645	19,561	21,456	25,613	2,717	14,946	17,856	19,717	21,558	25,618
50,000	3,019	9,692	12,901	14,930	16,939	20,965	3,019	9,854	13,030	15,005	16,963	20,889
55,000	3,321	4,691	8,165	10,307	12,431	16,689	3,321	4,769	8,211	10,302	12,376	16,539
60,000	3,622	1,047	3,437	5,692	7,930	12,421	3,622	1,064	3,401	5,607	7,797	12,196
65,000	3,924	0	968	2,385	4,736	9,460	3,924	0	889	2,242	4,548	9,184
70,000	4,226	0	1,000	1,878	2,740	7,554	4,226	0	918	1,724	2,516	7,244
75,000	4,528	0	1,029	1,906	2,767	5,649	4,528	0	945	1,749	2,541	5,304
80,000	4,830	0	1,058	1,933	2,795	4,480	4,830	0	971	1,775	2,566	4,113
85,000	5,132	0	1,087	1,961	2,822	4,506	5,132	0	998	1,800	2,591	4,137
90,000	5,434	0	1,117	1,989	2,849	4,533	5,434	0	1,025	1,826	2,616	4,161
95,000	5,735	0	1,146	2,016	2,876	4,559	5,735	0	1,052	1,851	2,641	4,186
100,000	6,037	0	1,175	2,044	2,904	4,586	6,037	0	1,079	1,876	2,666	4,210
110,000	6,641	0	1,218	2,084	2,943	4,624	6,641	0	1,118	1,914	2,702	4,245
120,000	7,245	0	1,260	2,125	2,983	4,663	7,245	0	1,157	1,951	2,739	4,281
130,000	7,848	0	1,312	2,165	3,023	4,701	7,848	0	1,204	1,988	2,775	4,316
140,000	8,452	0	1,352	2,206	3,063	4,740	8,452	0	1,241	2,025	2,812	4,351
150,000	9,056	0	1,393	2,246	3,103	4,779	9,056	0	1,279	2,062	2,849	4,387
160,000	9,660	0	1,433	2,287	3,143	4,817	9,660	0	1,316	2,099	2,885	4,422
170,000	10,263	0	1,474	2,327	3,183	4,856	10,263	0	1,353	2,137	2,922	4,458
180,000	10,867	0	1,514	2,368	3,223	4,895	10,867	0	1,390	2,174	2,959	4,494
190,000	11,471	0	1,555	2,409	3,263	4,933	11,471	0	1,428	2,211	2,995	4,529
200,000	12,075	0	1,596	2,449	3,302	4,972	12,075	0	1,465	2,249	3,032	4,565
210,000	12,678	0	1,636	2,490	3,340	5,011	12,678	0	1,502	2,286	3,067	4,600
220,000	13,282	0	1,677	2,531	3,379	5,050	13,282	0	1,540	2,323	3,102	4,636
230,000	13,886	0	1,718	2,571	3,417	5,088	13,886	0	1,577	2,361	3,137	4,672
240,000	14,489	0	1,759	2,612	3,455	5,127	14,489	0	1,614	2,398	3,172	4,707
250,000	15,093	0	1,799	2,653	3,493	5,166	15,093	0	1,652	2,435	3,207	4,743
260,000	15,697	17	1,840	2,693	3,532	5,205	15,697	15	1,689	2,472	3,242	4,779
270,000	16,301	59	1,881	2,733	3,570	5,244	16,301	54	1,727	2,509	3,277	4,814
280,000	16,904	101	1,922	2,773	3,608	5,283	16,904	93	1,764	2,546	3,313	4,850
290,000	17,508	143	1,952	2,813	3,647	5,322	17,508	132	1,792	2,583	3,348	4,886
300,000	18,112	186	1,993	2,854	3,685	5,361	18,112	171	1,830	2,620	3,383	4,922

Table D.2
Mica Hydropower Penalties Part 2

Combined Mica and Revelstoke Hydropower Penalties in Thousands of Dollars											
Storage Status	Normal Full	3/4 Full by elev.	1/2 Full by elev.	1/4 Full by elev.	Minimum Pool		Normal Full	3/4 Full by elev.	1/2 Full by elev.	1/4 Full by elev.	Minimum Pool
Elev. (ft)	2,475	2,423	2,398	2,372	2,320		2,475	2,423	2,398	2,372	2,320
Stor. (KAF)	20,076	14,936	12,869	11,022	8,022		20,076	14,936	12,869	11,022	8,022
Release (KAF/mo.)	Months April, May, and October					Release (KAF/mo.)	Months June, July, August, and September				
0	65,314	65,403	66,160	66,899	68,356	0	64,959	65,040	65,738	66,420	67,764
302	59,553	60,099	60,998	61,867	63,598	302	59,228	59,753	60,592	61,403	63,019
604	53,855	54,860	55,894	56,900	58,904	604	53,562	54,530	55,503	56,451	58,340
906	48,152	49,489	50,660	51,805	54,090	906	47,890	49,184	50,294	51,380	53,549
1,207	42,467	44,135	45,443	46,727	49,294	1,207	42,236	43,856	45,103	46,327	48,776
1,509	36,800	38,799	40,245	41,668	44,516	1,509	36,599	38,546	39,929	41,291	44,021
1,811	31,150	33,481	35,064	36,626	39,756	1,811	30,980	33,253	34,773	36,274	39,283
2,113	25,490	28,131	29,852	31,552	34,964	2,113	25,351	27,930	29,587	31,226	34,516
2,415	20,157	22,790	24,649	26,489	30,183	2,415	20,047	22,616	24,411	26,188	29,759
2,717	15,028	17,886	19,685	21,466	25,411	2,717	14,946	17,737	19,472	21,191	25,011
3,019	9,908	13,030	14,945	16,844	20,655	3,019	9,854	12,906	14,757	16,592	20,279
3,321	4,795	8,183	10,214	12,229	16,278	3,321	4,769	8,083	10,049	12,001	15,925
3,622	1,070	3,344	5,491	7,623	11,910	3,622	1,064	3,269	5,350	7,418	11,578
3,924	0	815	2,105	4,354	8,878	3,924	0	752	1,981	4,165	8,562
4,226	0	842	1,582	2,308	6,925	4,226	0	776	1,458	2,128	6,617
4,528	0	867	1,605	2,331	4,973	4,528	0	799	1,480	2,149	4,674
4,830	0	891	1,628	2,354	3,773	4,830	0	822	1,501	2,170	3,479
5,132	0	916	1,651	2,377	3,795	5,132	0	844	1,523	2,191	3,500
5,434	0	940	1,675	2,400	3,818	5,434	0	867	1,544	2,213	3,520
5,735	0	965	1,698	2,422	3,840	5,735	0	890	1,566	2,234	3,541
6,037	0	990	1,721	2,445	3,862	6,037	0	912	1,587	2,255	3,561
6,641	0	1,025	1,755	2,479	3,894	6,641	0	946	1,619	2,286	3,591
7,245	0	1,061	1,790	2,513	3,927	7,245	0	979	1,650	2,317	3,621
7,848	0	1,105	1,824	2,546	3,959	7,848	0	1,019	1,682	2,348	3,651
8,452	0	1,139	1,858	2,580	3,992	8,452	0	1,050	1,713	2,379	3,681
9,056	0	1,173	1,892	2,613	4,024	9,056	0	1,082	1,744	2,410	3,711
9,660	0	1,207	1,926	2,647	4,057	9,660	0	1,113	1,776	2,441	3,741
10,263	0	1,241	1,960	2,681	4,090	10,263	0	1,145	1,807	2,472	3,771
10,867	0	1,275	1,994	2,714	4,122	10,867	0	1,176	1,839	2,503	3,801
11,471	0	1,310	2,029	2,748	4,155	11,471	0	1,208	1,871	2,534	3,831
12,075	0	1,344	2,063	2,781	4,187	12,075	0	1,239	1,902	2,565	3,861
12,678	0	1,378	2,097	2,813	4,220	12,678	0	1,271	1,934	2,594	3,891
13,282	0	1,412	2,131	2,845	4,253	13,282	0	1,302	1,965	2,624	3,921
13,886	0	1,447	2,166	2,878	4,285	13,886	0	1,334	1,997	2,653	3,952
14,489	0	1,481	2,200	2,910	4,318	14,489	0	1,366	2,029	2,683	3,982
15,093	0	1,515	2,234	2,942	4,351	15,093	0	1,397	2,060	2,713	4,012
15,697	14	1,550	2,268	2,974	4,384	15,697	13	1,429	2,091	2,743	4,042
16,301	50	1,584	2,302	3,007	4,417	16,301	46	1,461	2,122	2,772	4,072
16,904	85	1,619	2,336	3,039	4,449	16,904	79	1,492	2,154	2,802	4,103
17,508	121	1,644	2,369	3,071	4,482	17,508	111	1,516	2,185	2,832	4,133
18,112	156	1,679	2,403	3,103	4,515	18,112	144	1,548	2,216	2,862	4,163

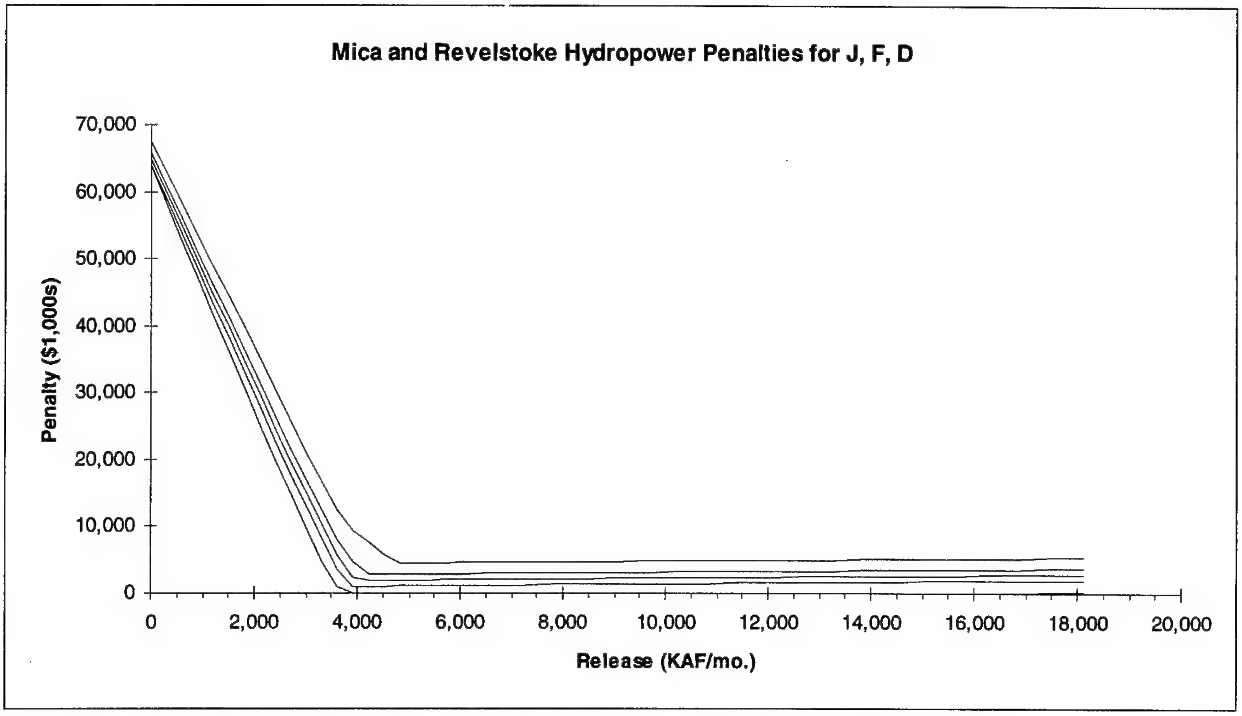

FIGURE D.1 Hydropower Penalties for January, February, and December

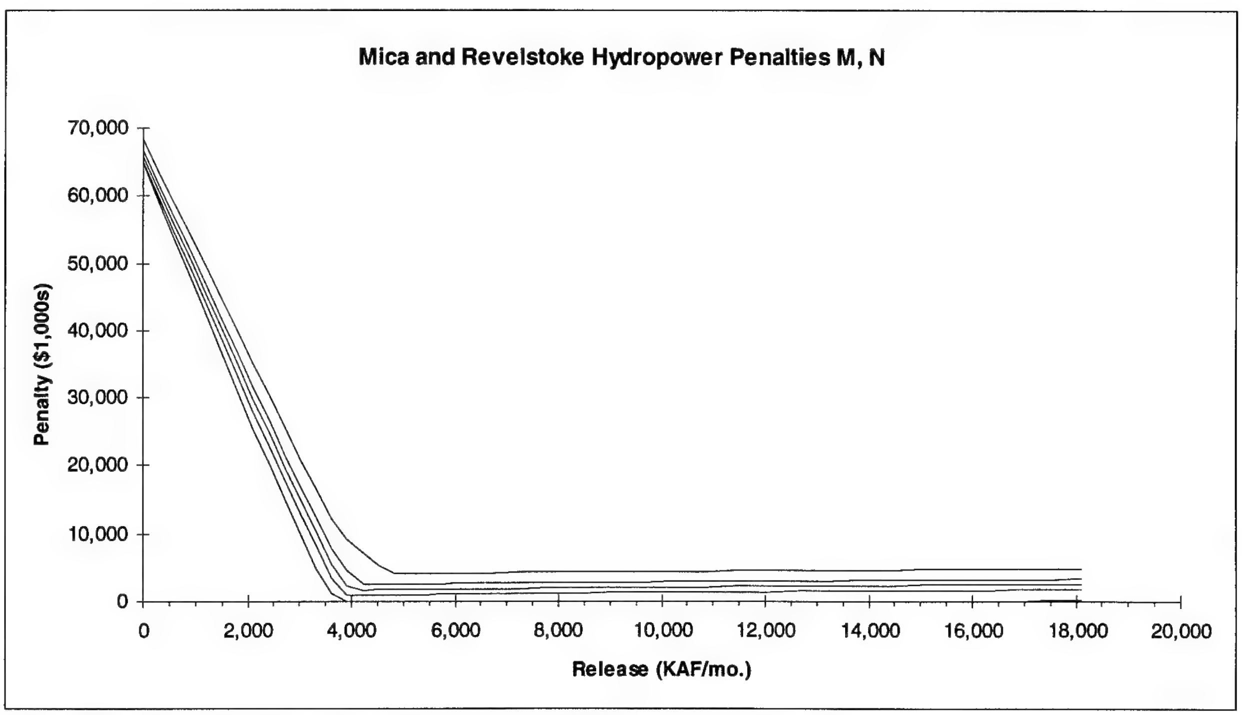

FIGURE D.2 Hydropower Penalties for March and November

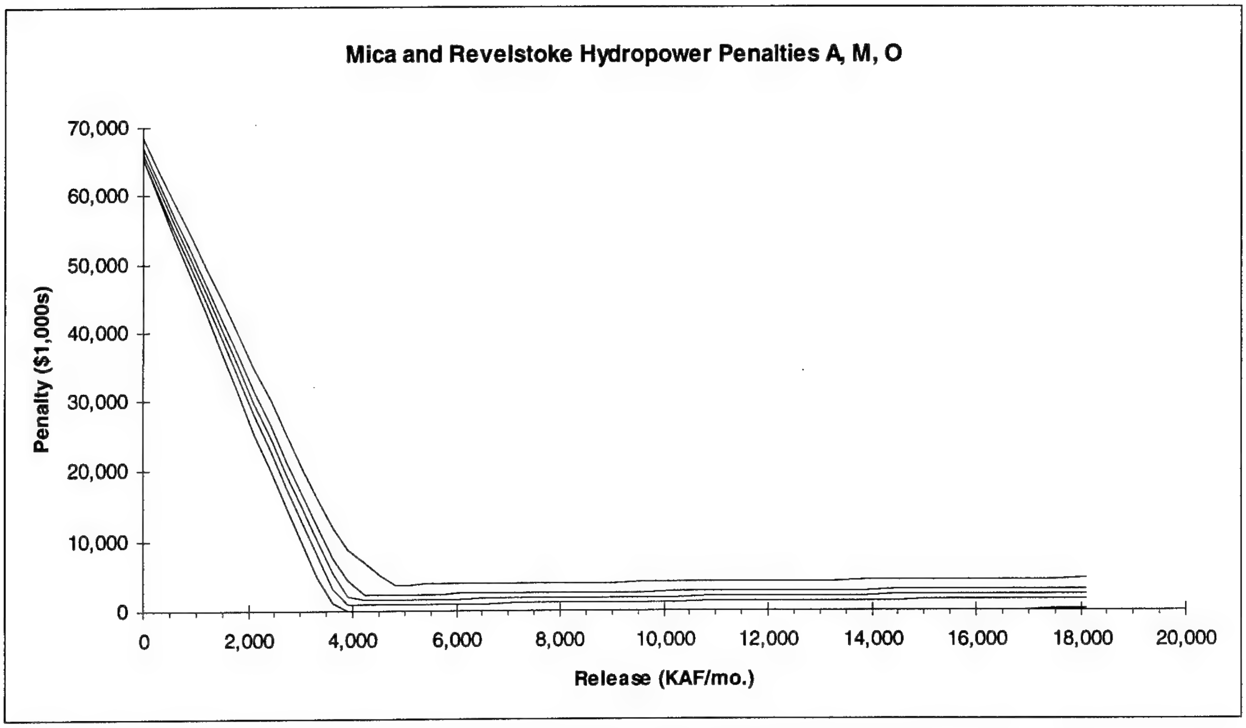

FIGURE D.3 Hydropower Penalties for April, March, and October

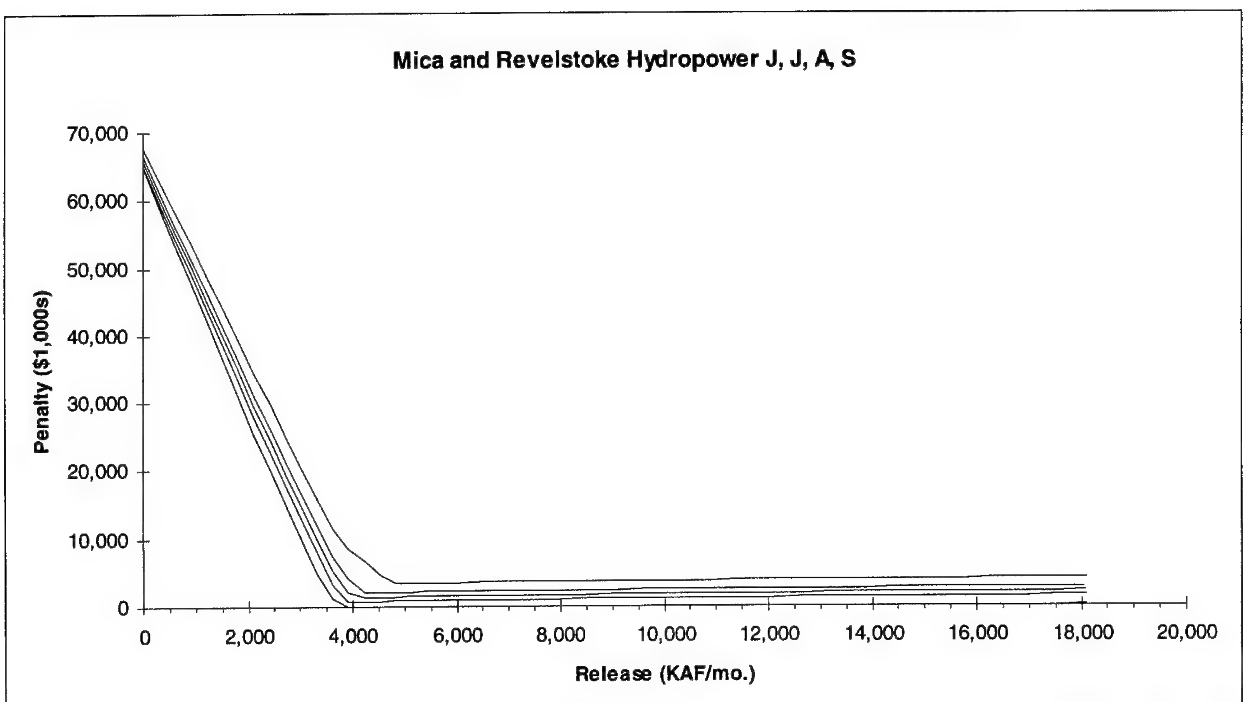

FIGURE D.4 Hydropower Penalties for June, July, August, and September

Table D.3
Revised Libby Storage Penalties

Revised Libby Storage Penalties In Thousands of Dollars							
Recreation Penalties for Canadian Portion from NPD							
Storage (KAF)	April	May	June	July	August	Sept.	October
0							
861.3	7.8	38.0	70.9	146.7	143.6	19.6	5.1
4016.5	2.7	13.0	24.3	50.2	49.2	6.7	1.7
5020.5	1.0	4.7	8.8	18.3	17.9	2.4	0.6
5237.1	0.7	3.5	6.5	13.4	13.1	1.8	0.5
5869.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Composite Penalty Function (adding Canadian Portion)							
Storage (KAF)	April	May	June	July	August	Sept.	October
0							
861.3	15.8	49.0	94.9	193.7	178.6	34.6	10.1
4016.5	10.7	24.0	48.3	97.2	84.2	21.7	6.7
5020.5	4.0	9.1	21.9	43.7	36.3	8.1	2.3
5237.1	2.7	6.5	17.5	34.4	28.1	5.8	1.5
5869.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Edited Penalty Functions							
Storage (KAF)	April	May	June	July	August	Sept.	October
0	25.3	62.9	153.0	307.9	266.7	56.0	15.9
861.3	21.6	53.7	130.5	262.7	227.6	47.8	13.6
4016.5	8.0	19.9	48.3	97.2	84.2	17.7	5.0
5020.5	3.7	9.1	22.1	44.5	38.6	8.1	2.3
5237.1	2.7	6.8	16.5	33.2	28.7	6.0	1.7
5869.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: Libby penalties for January, February, March, November, and December were not changed. No Canadian recreation penalties were supplied for these months.

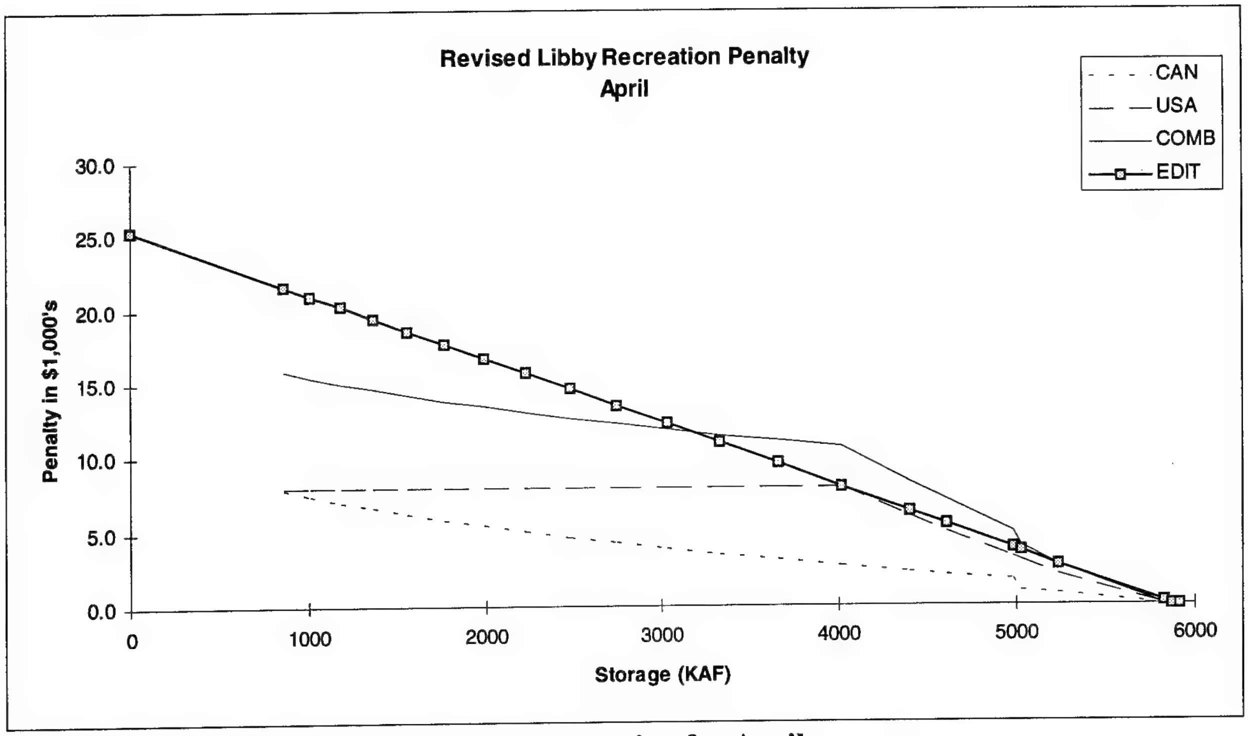

FIGURE D.5 Libby Recreation Penalty Function for April

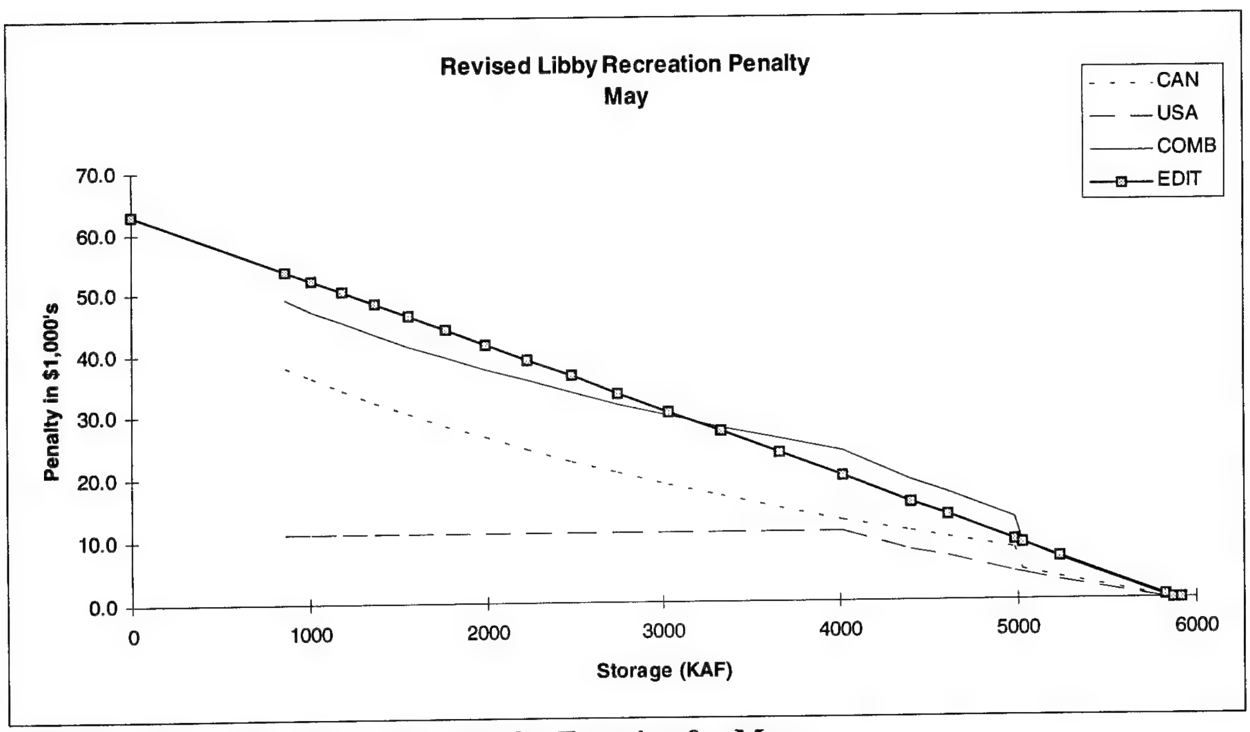

FIGURE D.6 Libby Recreation Penalty Function for May

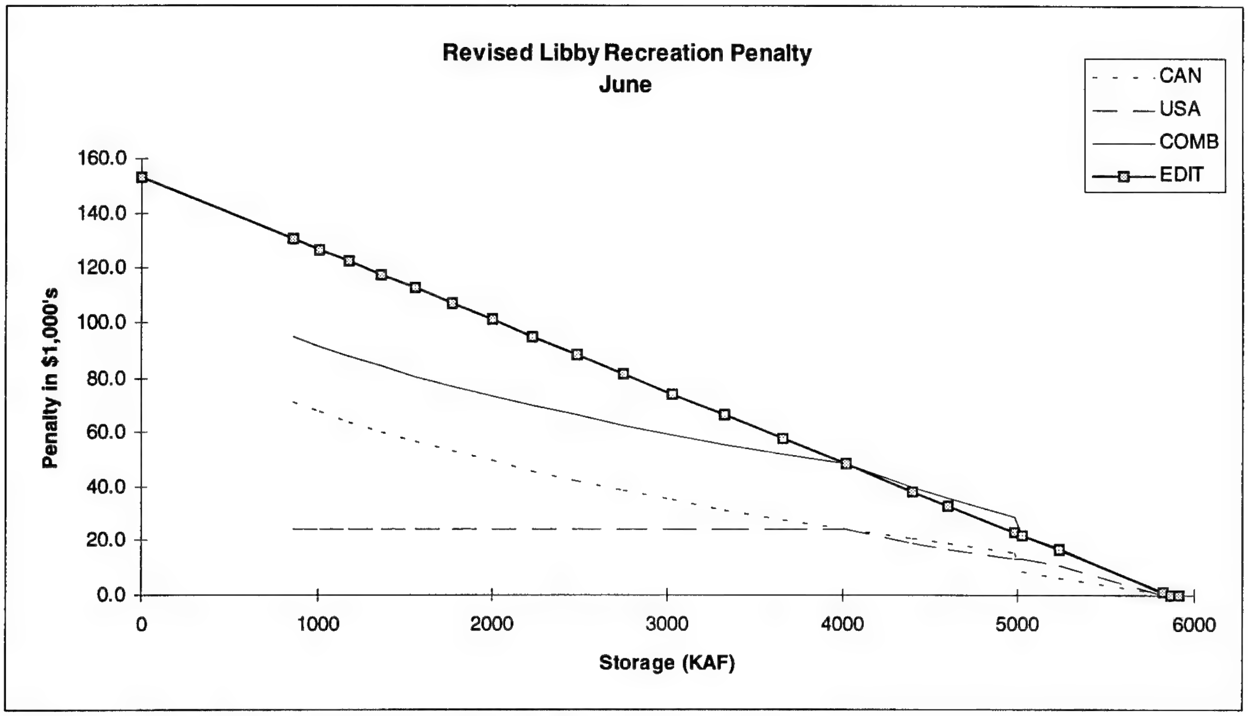

FIGURE D.7 Libby Recreation Penalty Function for June

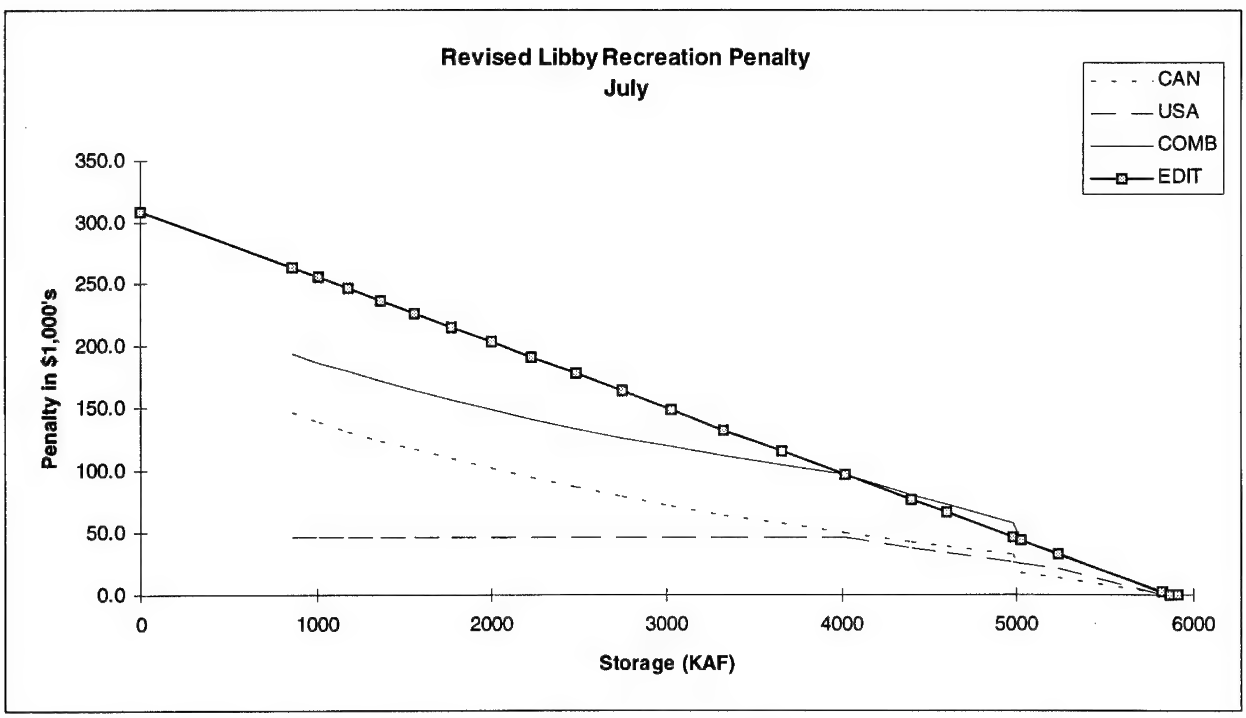

FIGURE D.8 Libby Recreation Penalty Function for July

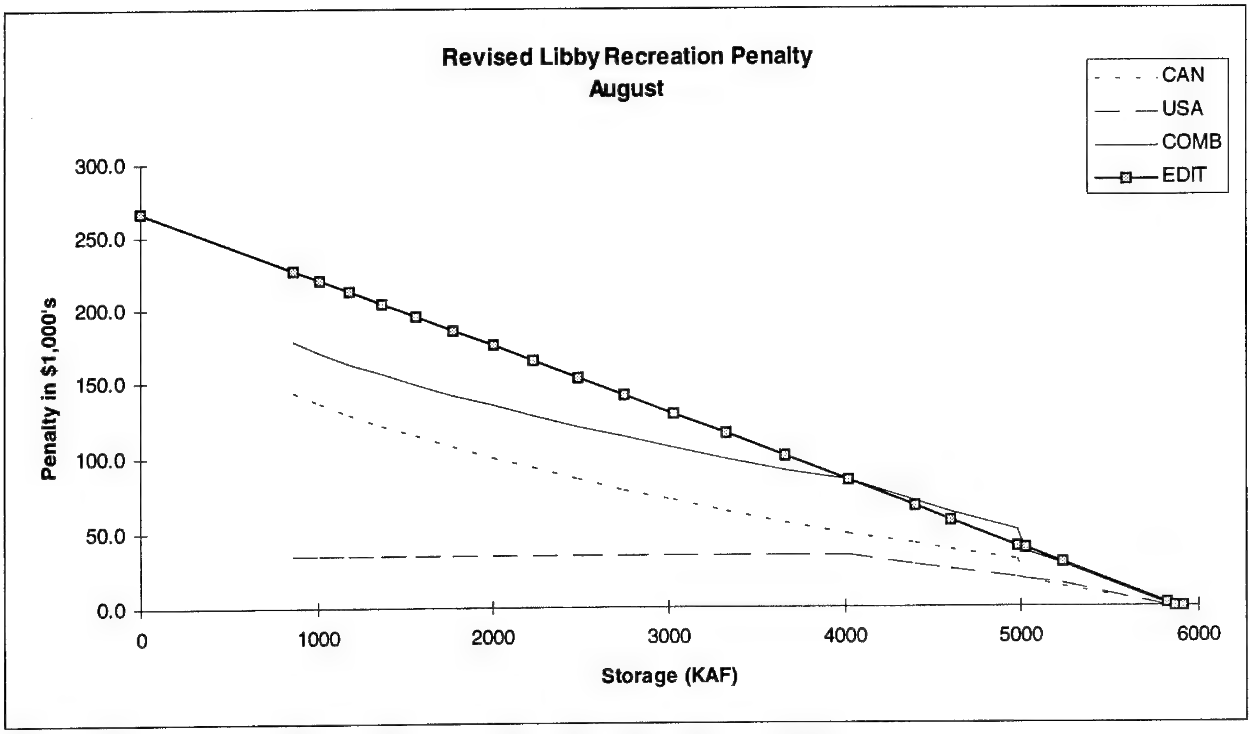

FIGURE D.9 Libby Recreation Penalty Function for August

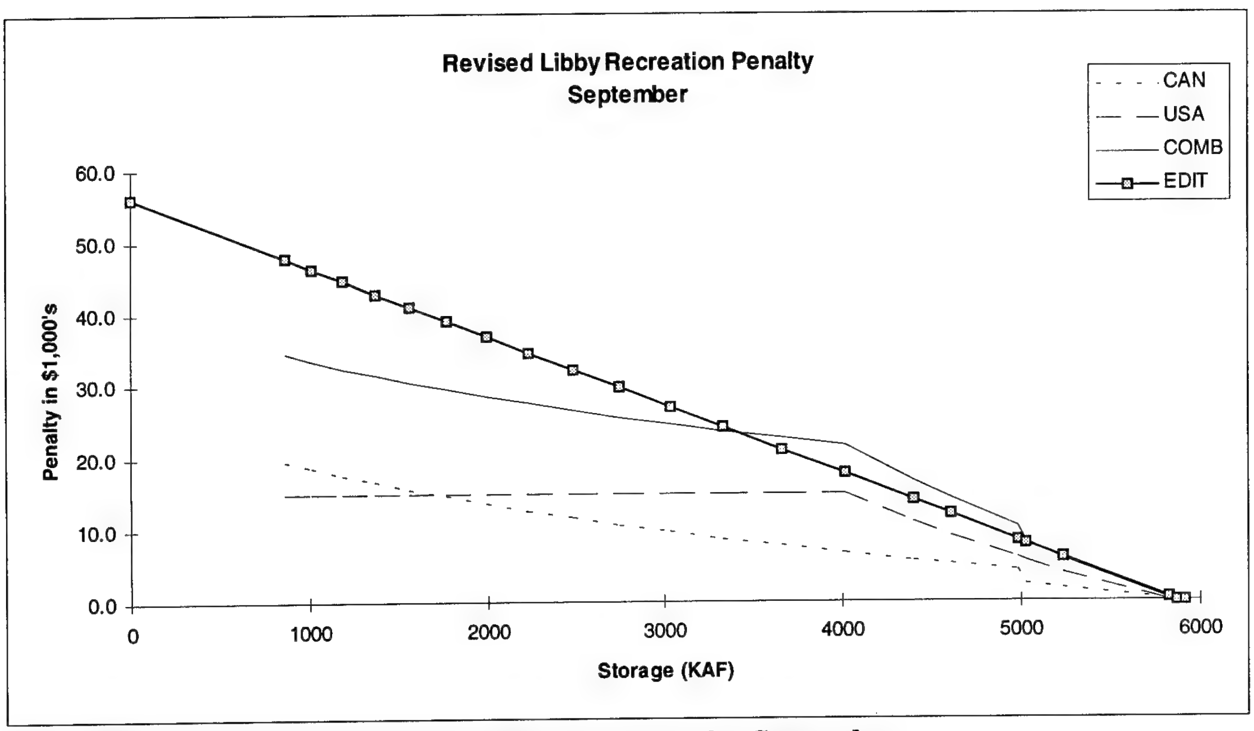

FIGURE D.10 Libby Recreation Penalty Function for September

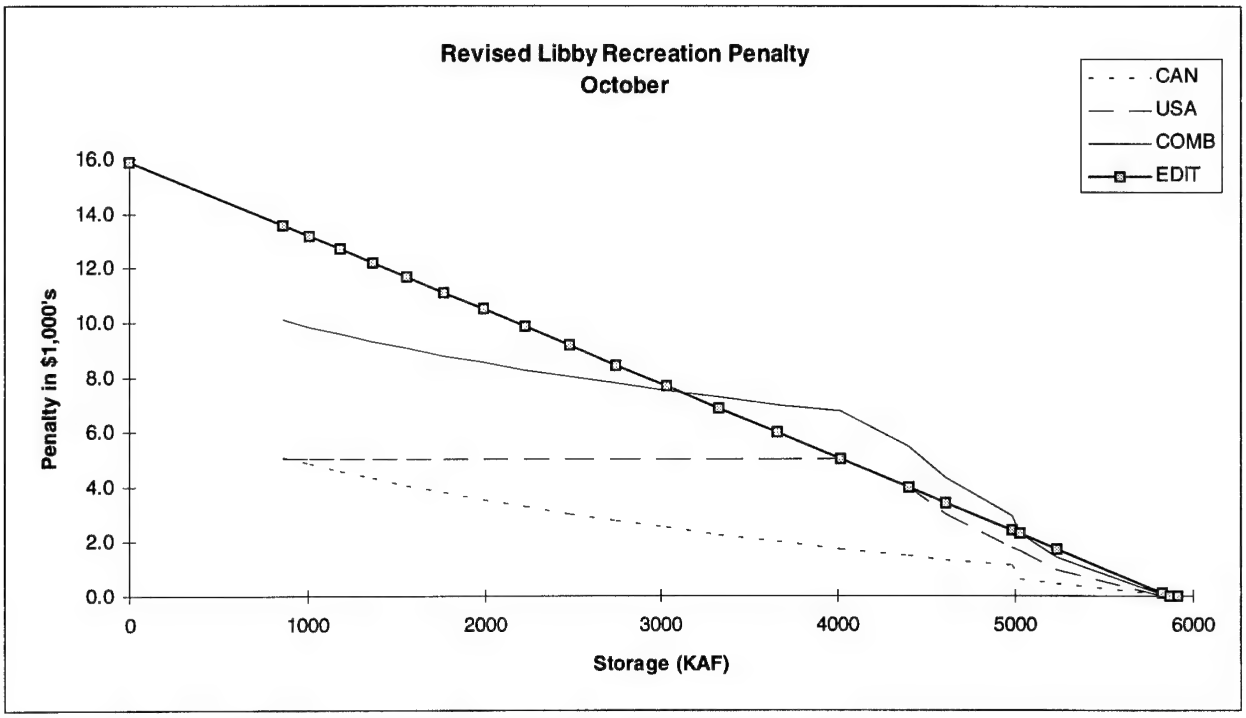

FIGURE D.11 Libby Recreation Penalty Function for October

Table D.4
Revised Spalding Flow Penalties

Revised Spalding Flow Penalties
In Thousands of Dollars

Recreation Fishing Penalty Function from NPD

Flow (KAF/mo)	Jan.	Feb.	March	April	Sept.	October	Nov.	Dec.	Flow(cfs)
0	991	825	851	190	44	1,175	1,918	1,054	0
121	0	0	0	0	0	0	0	0	2,000
1207	0	0	0	0	0	0	0	0	20,000
2414	991	825	851	190	44	1,175	1,918	1,054	40,000
7500	991	825	851	190	44	1,175	1,918	1,054	124,275

Composite Penalty Function (adding Phase II flood penalty)

Flow (KAF/mo)	Jan.	Feb.	March	April	Sept.	October	Nov.	Dec.	Flow(cfs)
0	991	825	851	190	44	1,175	1,918	1,054	0
121	0	0	0	0	0	0	0	0	2,000
1207	0	0	0	0	0	0	0	0	20,000
2414	991	825	851	190	44	1,175	1,918	1,054	40,000
5490	991	825	851	190	44	1,175	1,918	1,054	90,969
7500	669,877	669,711	669,737	669,076	668,930	670,061	670,804	669,940	124,275

Edited Penalty Functions

Flow (KAF/mo)	Jan.	Feb.	March	April	Sept.	October	Nov.	Dec.	Flow(cfs)
0	991	825	851	190	44	1,175	1,918	1,054	0
121	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	2,000
1207	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20,000
2414*	991	825	851	190	44	1,175	1,918	1,054	40,000
5490	2,526	2,102	2,169	484	112	2,994	4,888	2,686	90,969
7500	669,877	669,711	669,737	669,076	668,930	670,061	670,804	669,940	124,275

* = fishery flow break point where recreation ends, not included in entered penalty function
Spalding penalties for May, June, July, and August were not changed from Phase II.
There are no fishing penalties for these months.

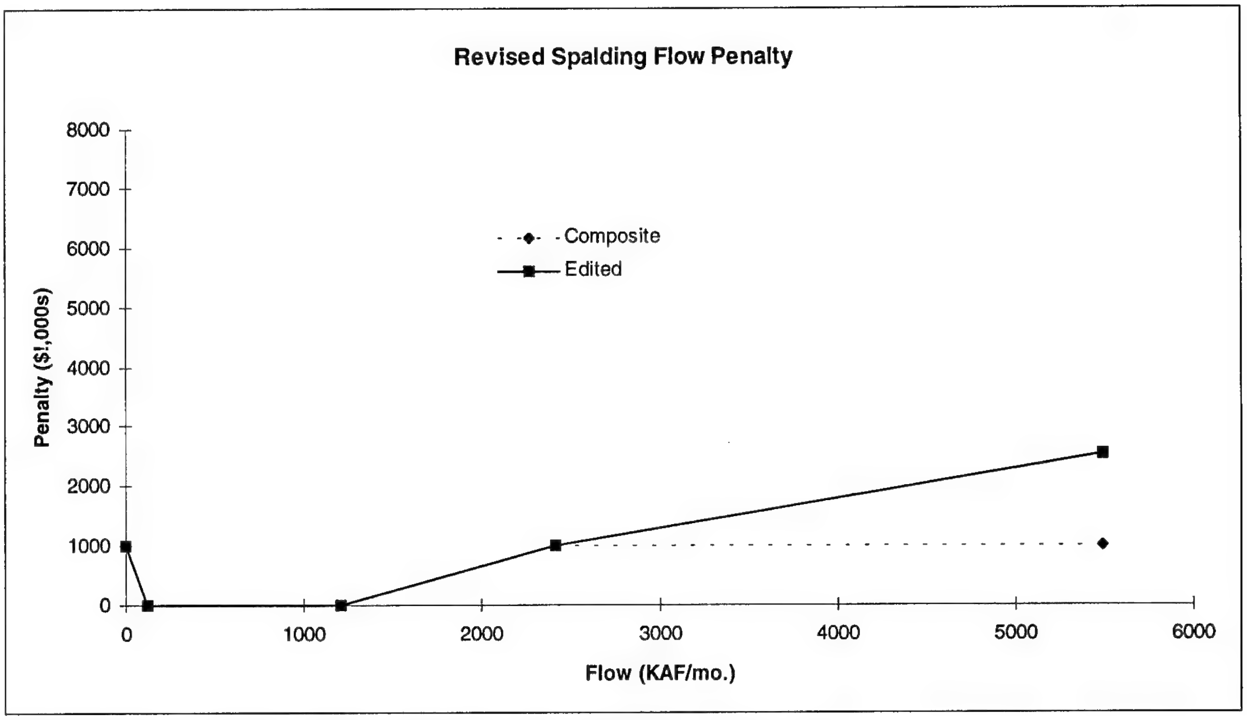

FIGURE D.12 Revised Spalding Flow Penalty for all Months

Table D.5
System Wide Hydropower

Average Flows at Dalles for Critical Period			
	Flow (cfs-mon)	Flow (KAF) @y=0	Cost (K$) @x=0
Jul	124,682	7,527	590,694
Aug1	121,337	7,325	574,846
Aug2	114,939	6,939	544,535
Sep	101,973	6,156	483,107
Oct	114,370	6,905	541,840
Nov	127,652	7,707	604,764
Dec	139,188	8,403	659,417
Jan	141,335	8,533	669,589
Feb	132,298	7,987	626,775
Mar	136,094	8,216	644,759
Apr1	136,062	8,214	644,608
Apr2	164,797	9,949	780,743
May	155,908	9,413	738,630
Jun	171,226	10,337	811,201

Appendix E

Methodologies in Annual Operation Applications of HEC-PRM

This appendix describes some of the detailed methodologies investigated and used for the annual operation application of HEC-PRM described in Chapter 6.

E.1 Development of Annual Inflow Weights with Forecast Information

During the January to July operating period on the Columbia River System, the state of the runoff conditions of the season becomes increasingly clear. As snowpack conditions develop, the coming season's inflows should begin to seem more like those of some previous years and less like other years. This section describes a method for initially quantifying the relative likelihood of each year of inflows from the historic record. The resulting quantitative weights might be modified, based on the collective experience of the system's operating staff. Modification of these weights is desirable particularly later in the season, as it becomes impossible for the current year to be like some (particularly low-flow) previous years.

The approach assigns relative weights to each year of historical inflows, based on forecast January-July runoff volumes and actual January-July runoff volumes for those years, as well as current runoff forecasts. The sum of weights for all years equals one.

Conceptually, the approach assigns weights based on the relative distance of each historical year's forecast and actual runoff from that of a perfect runoff forecast, on a plot of forecast versus actual runoff (Figure E.1). The assignment of weights is accomplished by the equations below:

$$D_i = \sqrt{(A_i - F_c)^2 + (F_i - F_c)^2} \tag{E.1}$$

$$w = \frac{1}{\sum \frac{1}{D_i}} \tag{E.2}$$

$$W_i = w * D_i \tag{E.3}$$

where:

Di	=	distance (in MAF) from forecast point to forecast-actual point from year i,
Fc	=	current runoff forecast (at The Dalles),
Fi	=	forecast for historical inflow year i,
Ai	=	actual runoff for historical inflow year i,
w	=	constant which makes all year weights sum to one, and
Wi	=	relative weight for each historical inflow year i.

Using this method, relative weights were assessed to each inflow year for January 1, 1994 (a current forecast of 80 MAF). These weights appear in Table E.1 and Figure E.2.

While the method is simple and would seem to have some basis in common sense, it is not rigorous in a fundamental sense. There is no explicit basis for inferring probabilities from these rough relative likelihood weights. The behavior of this weighting scheme is somewhat unstable with respect to forecasts. Small changes in forecast flows often lead to large changes in the weights given to each annual flow record. While this problem detracts from this particular weighting scheme, some other weighting scheme, perhaps more rigorously derived, might be useful for developing probabilistic interpretations to different annual inflow records.

Hirsch (1981a) describes a somewhat less precise (but perhaps equally accurate) method applied by the National Weather Service for incorporating forecasts into probabilistic assessments. Forecast information is used to classify each historical year's record into one of three categories: analog (like the present year), anti-analog (unlike the present year), and unclassified. Probability weights are then assessed so that probabilities for analog years are twice those of unclassified years, which are twice those of anti-analog years, with all weights summing to one.

E.2 Estimating Storage Penalties for Final Period of Analysis

For the seasonal operation runs, a penalty was imposed on end-of-analysis-period storage for each storage reservoir. This avoided imposing a requirement that the system achieve a given level of storage at the end of the analysis period, since the system should not completely refill in all years. A high penalty was assessed for zero end-of-period storage, decreasing linearly to zero at a target storage level. End of July target storages for this system are typically full reservoir conditions, and were supplied by NPD staff.

Since the purpose of end-of-July storage for this system is typically to store energy for hydropower generation during the Fall and Winter, the slope of the end-of-July storage penalty was estimated to be a function of the energy content of each reservoir. The value of energy stored is a function of the quantity of water stored, the elevation at which it is stored, the unit value of energy, and the efficiency of hydropower generation. For this example, an efficiency of 0.85 and a value of power of 0.02 \$/KWH was assumed. This translates into a value of \$17/KAF of storage at a 1 ft. elevation. The corresponding values of storage and penalty function are given in Table E.2. These penalties were used only in the seasonal operation HEC-PRM runs.

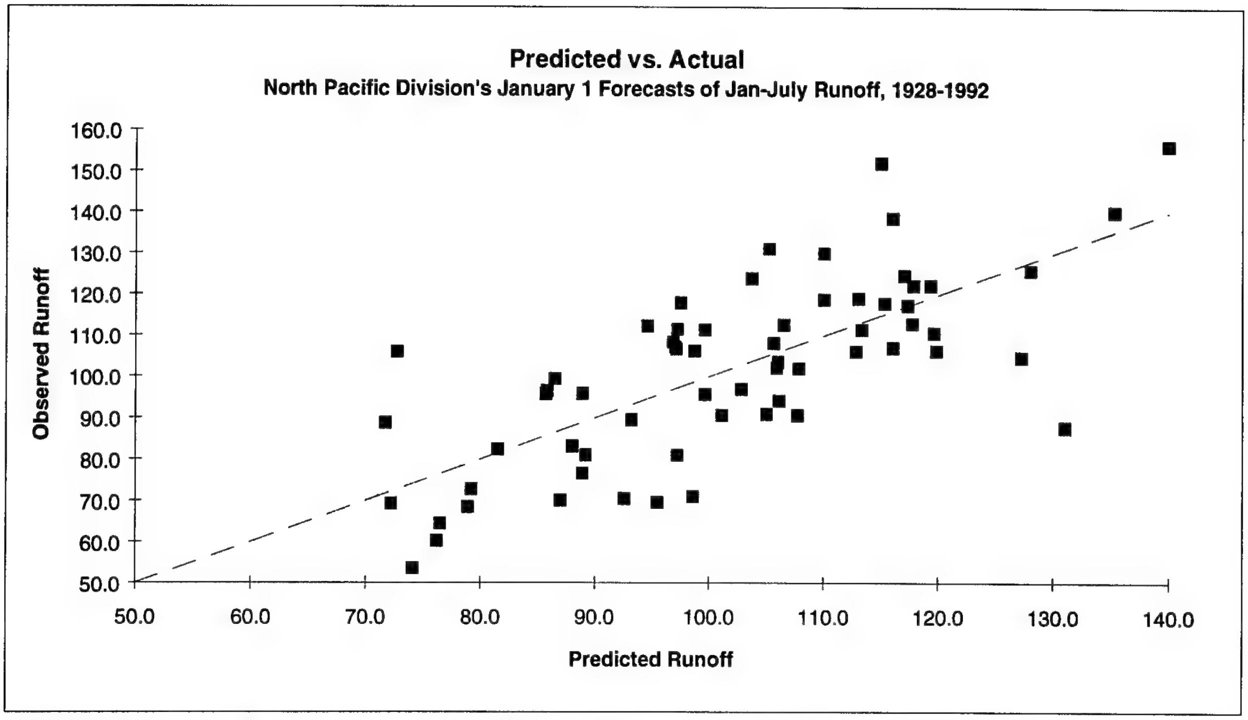

FIGURE E.1 Dalles January to July Flow (Forecast vs. Observed)

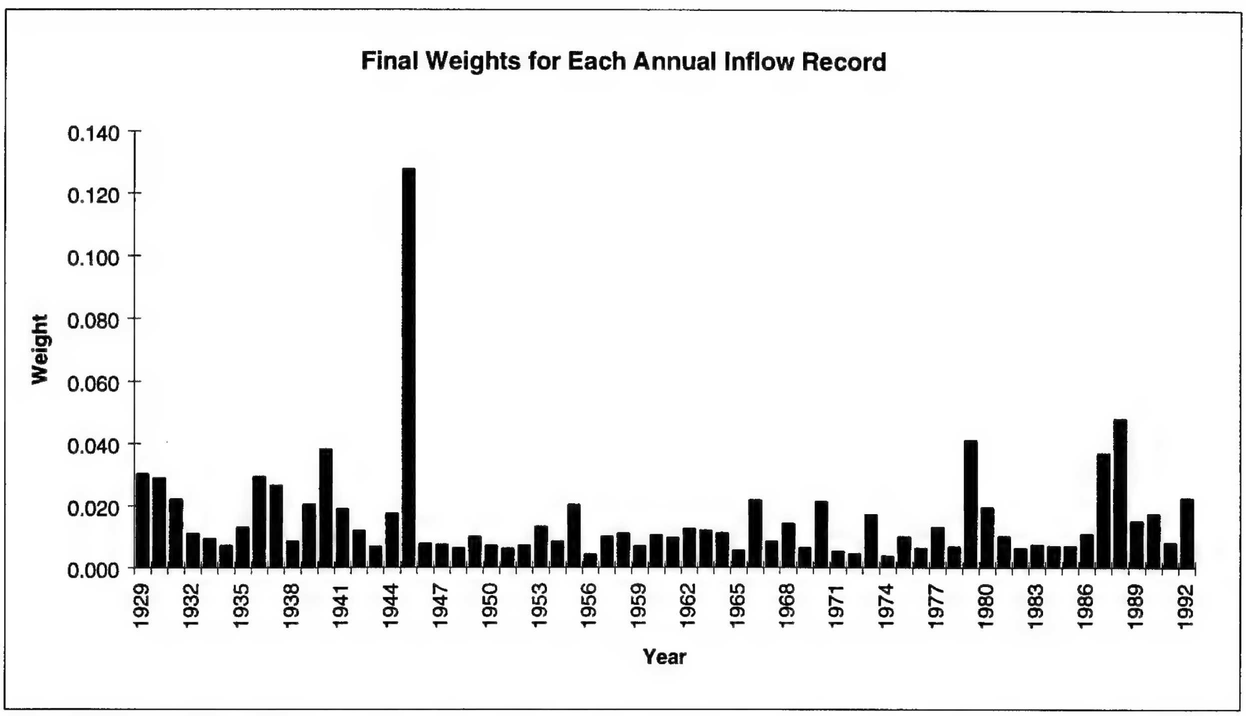

FIGURE E.2 Final Weights for Each Annual Inflow Record for Current Forecast of 80 KAF

Table E.1
Weight Values

	Historical Flow (MAF)		Weight Calculations		
Year	January Forecast	Observed Runoff	Distance to forecast pt.	1/ Distance	Final Weights
1929	78.9	68.4	11.7	0.086	0.030
1930	87.0	70.0	12.2	0.082	0.029
1931	76.5	64.4	16.0	0.063	0.022
1932	98.7	106.2	32.2	0.031	0.011
1933	105.6	108.1	38.0	0.026	0.009
1934	119.6	110.6	50.0	0.020	0.007
1935	105.0	90.9	27.3	0.037	0.013
1936	71.7	88.7	12.0	0.083	0.029
1937	72.2	69.2	13.3	0.075	0.026
1938	112.8	106.1	41.9	0.024	0.008
1939	97.2	81.0	17.2	0.058	0.020
1940	89.2	81.0	9.3	0.108	0.038
1941	95.5	69.5	18.7	0.053	0.019
1942	107.7	90.6	29.7	0.034	0.012
1943	117.3	117.3	52.8	0.019	0.007
1944	76.2	60.2	20.2	0.050	0.017
1945	81.5	82.3	2.7	0.364	0.128
1946	113.3	111.4	45.8	0.022	0.008
1947	119.8	106.2	47.6	0.021	0.007
1948	105.2	131.0	56.9	0.018	0.006
1949	107.8	101.9	35.4	0.028	0.010
1950	103.7	123.8	49.8	0.020	0.007
1951	117.0	124.5	57.9	0.017	0.006
1952	117.7	112.9	50.0	0.020	0.007
1953	72.7	105.8	26.8	0.037	0.013
1954	97.5	117.9	41.7	0.024	0.008
1955	85.8	96.4	17.4	0.057	0.020
1956	135.3	140.1	81.7	0.012	0.004
1957	94.6	112.3	35.4	0.028	0.010
1958	97.0	107.2	32.1	0.031	0.011
1959	115.3	117.8	51.7	0.019	0.007
1960	105.9	102.1	34.0	0.029	0.010
1961	99.6	111.3	36.9	0.027	0.009
1962	102.8	96.9	28.4	0.035	0.012
1963	106.1	94.1	29.7	0.034	0.012
1964	97.1	106.7	31.7	0.032	0.011
1965	128.0	125.7	66.3	0.015	0.005
1966	93.2	89.5	16.3	0.061	0.022
1967	106.5	112.6	42.0	0.024	0.008
1968	99.6	95.6	25.1	0.040	0.014
1969	117.8	122.1	56.6	0.018	0.006
1970	85.7	96.1	17.1	0.059	0.021
1971	116.0	138.5	68.7	0.015	0.005
1972	115.0	151.9	80.0	0.013	0.004
1973	98.6	70.9	20.7	0.048	0.017
1974	140.0	156.1	96.9	0.010	0.004
1975	97.2	111.4	35.8	0.028	0.010
1976	119.3	122.1	57.6	0.017	0.006
1977	74.1	53.5	27.1	0.037	0.013
1978	127.2	104.6	53.2	0.019	0.007
1979	88.0	83.1	8.6	0.117	0.041
1980	88.9	95.8	18.1	0.055	0.019
1981	106.0	103.5	35.0	0.029	0.010
1982	110.0	129.9	58.2	0.017	0.006
1983	110.0	118.7	49.0	0.020	0.007
1984	113.0	119.0	51.1	0.020	0.007
1985	131.0	87.7	51.6	0.019	0.007
1986	96.8	108.3	32.9	0.030	0.011
1987	88.9	76.5	9.6	0.105	0.037
1988	79.2	72.7	7.3	0.136	0.048
1989	101.1	90.6	23.6	0.042	0.015
1990	86.5	99.7	20.7	0.048	0.017
1991	116.0	107.0	45.0	0.022	0.008
1992	92.6	70.4	15.8	0.063	0.022
Aver.	101.8	101.5			
	Sums =		2286.1	2.852	1.000
	Max. Distance =		96.9		

Table E.2
Annual Operations End of Period Storage Penalties

Reservoir	Target Storage (KAF)	Hydropower Elevation (ft)	Hydropower Storage Value ($1,000/kaf)	Penalty for Zero Storage ($K)	Storage for Zero Penalty (KAF)
Mica	19045.0	2464.8	42.3	805,173	19045.0
Arrow	7327.3	1290.0	22.1	162,129	7327.3
Duncan	1422.8	1743.3	29.9	42,544	1422.8
Libby	5869.4	2459.0	42.2	247,559	5869.4
Corra Linn	5770.0	1743.3	29.9	172,534	5770.0
Grand Coulee	9107.4	1290.0	22.1	201,516	9107.4
Albeni Falls	1539.2	2062.5	35.4	54,452	1539.2
Kerr	1792.0	2893.0	49.6	88,923	1792.0
Hungry Horse	3647.1	3560.0	61.1	222,702	3647.1
Dworshak	3468.0	1600.0	27.4	95,176	3468.0
Granite	1825.0	738.8	12.7	23,127	1825.0
McNary	1300.0	338.8	5.8	7,555	1300.0
John Day	2366.7	265.0	4.5	10,758	2366.7

Note: Hydropower Elevation for Arrow and Duncan are those of the downstream reservoir.

Appendix F

Mass Balance Considerations: HEC-PRM vs. HYSSR

During the analysis of the PRM results, we noticed a difference in the total amount of water in the system between Alternative 0 (based on HYSSR output HM9091A2-SOR Base Case) and Alternative 7. There is a cumulative difference of approximately 182 million acre feet over the fifty years analyzed, an average of about 3.6 MAF/year (See Figure F.1). Our first attempt to identify the source of this discrepancy was to compare the inflow hydrology used for the two models. However, upon discussion with HEC personnel that created the original Alternative 0 data files, we discovered that the Alternative 0 data was generated from HYSSR output and therefore the inflow hydrology data is not available at HEC.

The next step taken was to compare the inflows supplied to HEC-PRM with the outflows and changes in storage for each month. This exercise showed the mass balance within the HEC-PRM model is quite good. The cumulative difference over the fifty year period was -1 KAF for *Inflows - Flow at the Dalles - Change in System Wide Storage*. The largest difference for any single month was 0.06 KAF, and the average difference was -0.0009 KAF (See Figure F.2).

Since the difference does not arise through the HEC-PRM algorithm, the difference must arise due to a difference in inflow hydrologies used for the two models, or from internal adjustments or diversions in the HYSSR model not accounted for in the HEC-PRM model. We derived the total inflow for the HYSSR model using a mass balance calculation (like the one discussed above) and compared it to the inflow hydrology used for HEC-PRM (Figure F.3). The monthly inflows are usually higher for PRM. The average monthly difference is 303 KAF with extremes of 2366 and -2368 KAF. However, during the late 1960's and early 1970's the inflows to HEC-PRM are sometimes much lower than for HYSSR.

This discrepancy should not significantly impact the overall results for the HEC-PRM model, but the cause of this difference should be determined and corrected if future HEC-PRM studies are conducted for the Columbia River System.

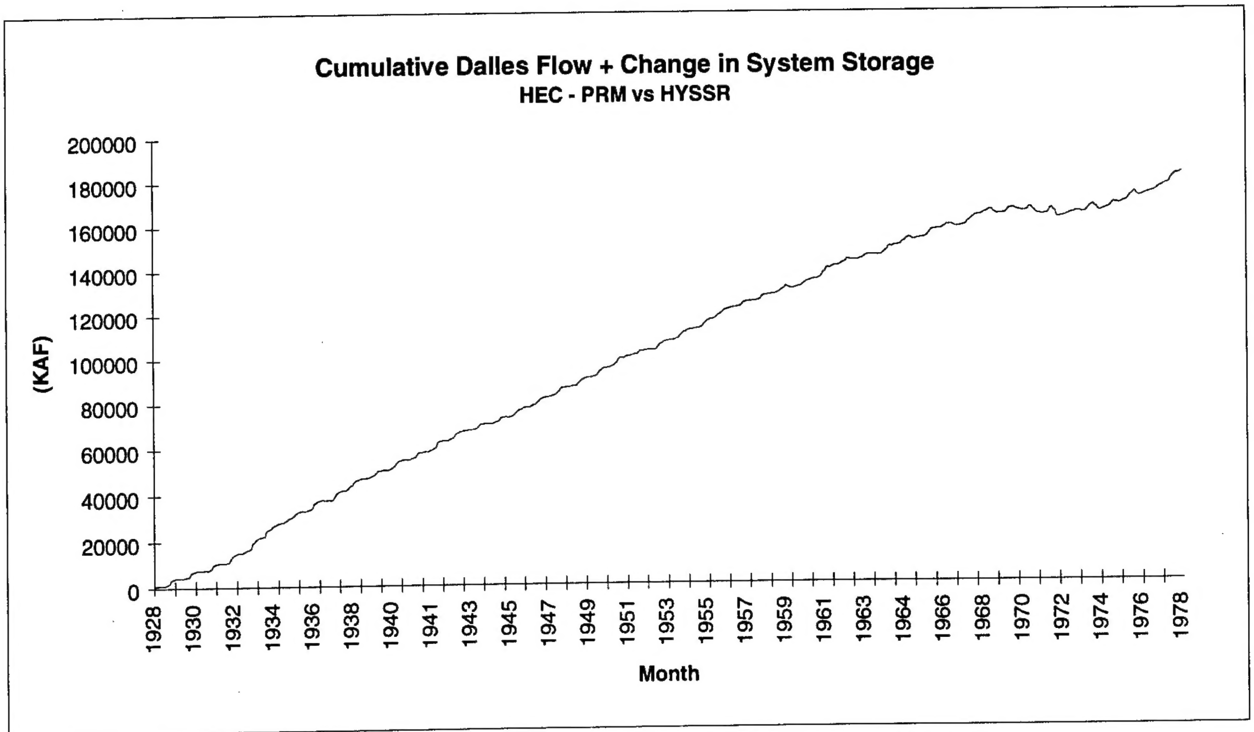

FIGURE F.1 Difference of Water in System (HEC-PRM vs. HYSSR)

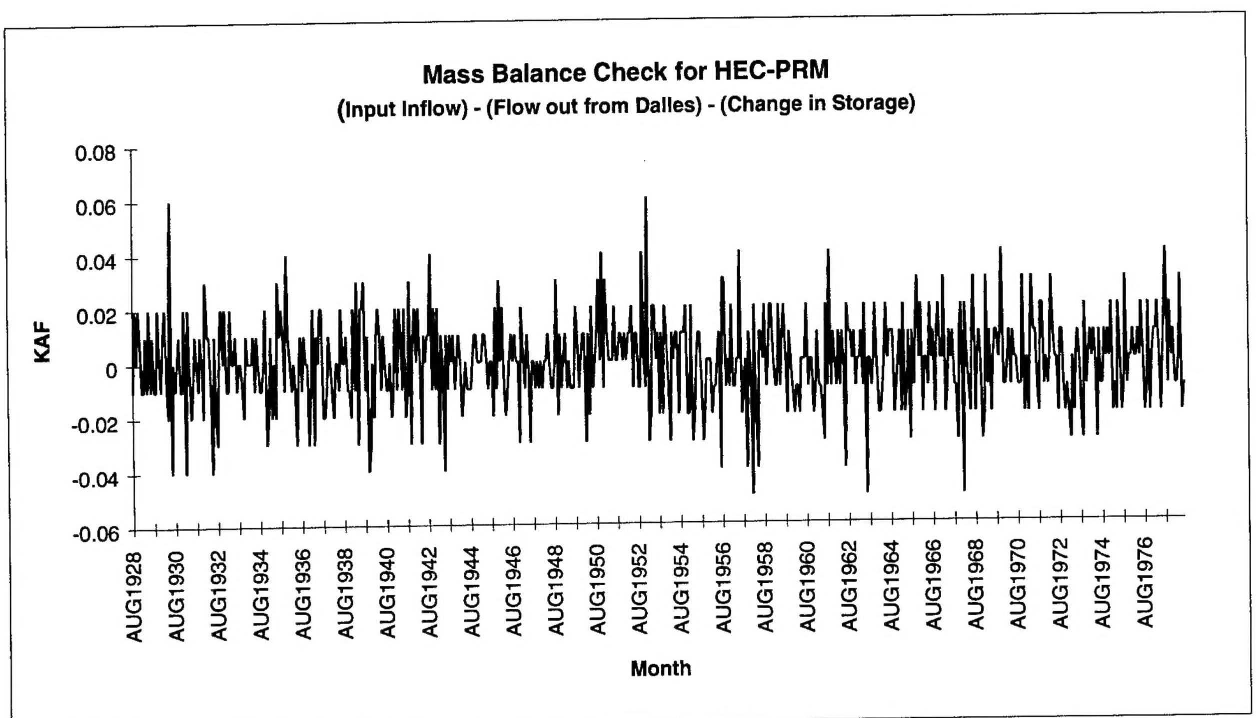

FIGURE F.2 Monthly Difference [Input Inflow - (Dalles Release + Change in System Storage)]

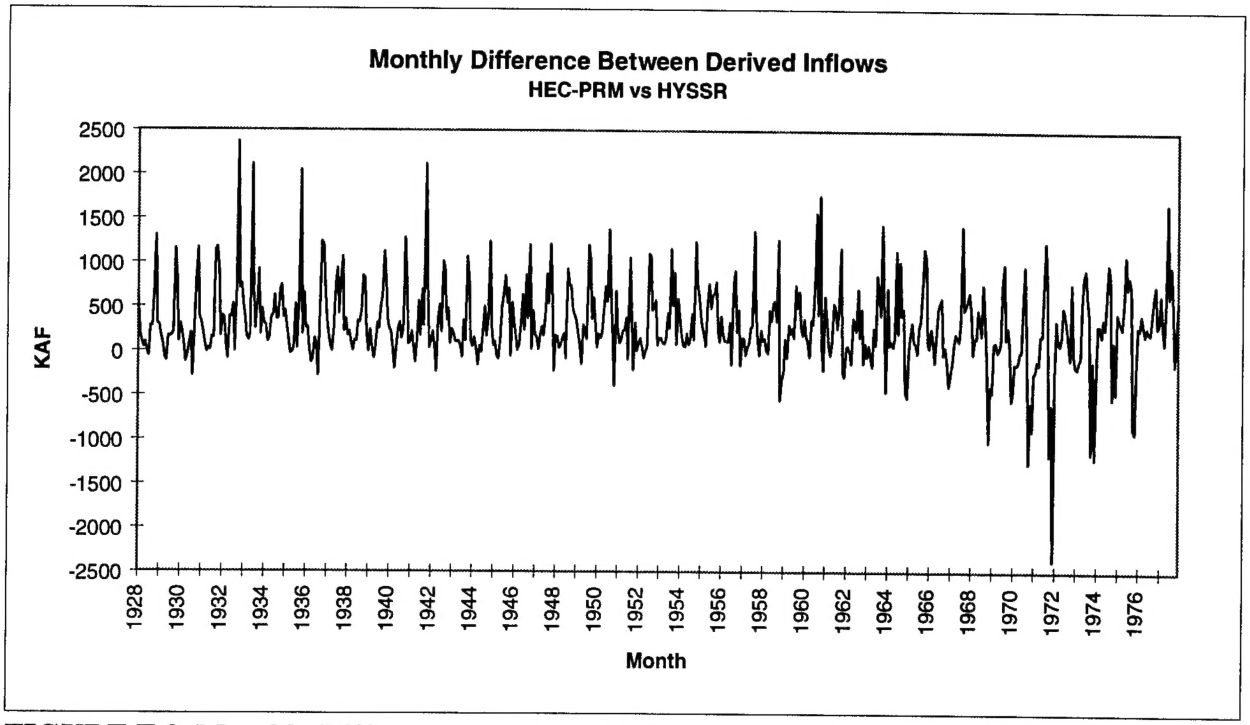

FIGURE F.3 Monthly Difference Between Calculated Inflows